NOAA Estuary-of-the-Month
Seminar Series No. 13

Galveston Bay: Issues, Resources, Status, and Management

February 1989

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NOAA Estuarine Programs Office

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Galveston Bay: Issues, Resources, Status, and Management

Proceedings of a Seminar
Held March 14, 1988
Washington, D.C.

U.S. DEPARTMENT OF COMMERCE
C. William Verity, Secretary

National Oceanic and Atmospheric Administration
William E. Evans, Under Secretary

NOAA Estuarine Programs Office
Virginia K. Tippie, Director

The NOAA Estuarine Programs Office
and
The U.S. Environmental Protection Agency
present

An Estuary-of-the-Month Seminar

Galveston Bay

Issues, Resources, Status, and Management

March 14, 1988

U.S. Department of Commerce
14th and Constitution Avenue, N.W.
Room 4830
Washington, D.C.

Acknowledgement

We gratefully acknowledge the assistance of Drs. Terry Whitledge of The University of Texas Marine Science Institute and Sammy Ray of Texas A&M University at Galveston, who had principal responsibility for assembling the speakers and whose familiarity with the bay area and its people were invaluable. The seminar was coordinated in Washington, D.C., by Catherine L. Mills, Estuarine Programs Office Regional Coordinator, with the help of other members of the EPO staff. We would also like to express our appreciation to the administrators and information staff of the Texas A&M University Sea Grant College Program, who produced both the Executive Summary and this final document.

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Questions concerning these proceedings may be directed to the NOAA Estuarine Programs Office by writing to Room 625 Universal South, 1825 Connecticut Avenue, N.W., Washington, D.C. 20235, or by calling (202) 673-5243.

Foreword

The following are the proceedings of a seminar on Galveston Bay, held on March 14, 1988, at the Herbert C. Hoover Building of the U.S. Department of Commerce in Washington, D.C. The Estuarine Programs Office (EPO) of the National Oceanic and Atmospheric Administration (NOAA) sponsored this seminar as a part of the continuing series of "Estuary-of-the-Month" Seminars, held with the objective of bringing to public attention important research and management issues of our nation's estuaries. To this end, participants first presented historical and scientific overviews of the bay area, followed by an examination of management issues by scientists and research managers involved in Galveston Bay.

Contents

Galveston Bay

Photo— Norman Martin, Texas Sea Grant Program

Preface

The Galveston Bay estuary is the second largest coastal embayment in the State of Texas and is surrounded by a population of nearly three million people in the Houston region. Galveston Bay has served the State of Texas by producing avenues for navigation, cooling water for industries, receptacle for discharges, playground for outdoor recreation and a pantry for seafood. All of these often conflicting uses have taken Galveston Bay close to the environmental precipice of degradation. Only with careful and prudent management can Galveston Bay be as "all-serving" in the future as it has in the past. It was this task of preserving the ecological balances in Galveston Bay that coalesced this group of concerned scientists and managers to present a holistic overview of what is known about the health of Galveston Bay, detail the multiple use conflicts and present a summary of research needs that would be useful for management. There is not enough room in the introduction to list all of the contributing organizations that provided the time and resources of their personnel to produce the Galveston Bay Seminar and the written texts (Appendix II). However, as organizers we would like to thank all of the participants for their contributions and congratulate them for a job well done. It was a pleasure interacting with university, local, state and federal agencies in striving for a common goal to preserve Galveston Bay.

Terry E. Whitledge
Sammy M. Ray
Co-Organizers,
Galveston Bay Seminar

Introduction

Sammy M. Ray and A.R. (Babe) Schwartz

In May 1987 the National Oceanic and Atmospheric Administration's Estuarine Programs Office invited Terry Whitledge and Sammy Ray to organize a seminar on Galveston Bay for presentation in the "Estuary-of-the-Month" seminar series. We immediately convened a meeting of about 30 individuals, representing federal, state, universities and private organizations to develop this seminar. Since May 1987 we have held several meetings involving representation from user groups and regulatory agencies to develop an objective presentation of the uses, values, conflicts and problems of one of the nation's most important estuarine systems. After several months of hard work by many individuals, we are pleased to have the opportunity to tell the "Galveston Bay" story in our nation's capital.

Although Texas does not have a formal Coastal Zone Management Program, the state has expended $5 million in a five-year effort to develop such a plan. This effort, while directly unsuccessful, has resulted in the enactment of several legislative measures relating to coastal environmental affairs, which began with the passage of the Open Beaches Act of 1958. With this landmark beginning, other major coastal environmental acts followed in rapid succession. These acts included the following:

- Texas Sea Grant Program — 1968
- Gulf Coast Waste Disposal Authority — 1969
- Texas Coastal and Marine Council — 1971
- Public Right to Freshwater Inflow — 1971
- Coastal Public Lands Management Act — 1973
- Texas Energy and Natural Resources Council — 1978

Each of these legislative actions, as well as other related acts, leaves no doubt that Texas has been more active in protecting its coastal environment than the *lack* of a formal Coastal Zone Management Program indicates. The passage of the Coastal Public Lands Management Act of 1973 is noteworthy in that, for the first time, it provided a mechanism for the comprehensive management of all state-owned submerged lands (1.75 million acres) in the bays and estuaries of Texas. As a part of the public lands management program, a submerged lands inventory depicting wetlands, oyster reefs, rookeries, sediment types, habitat assemblages, petroleum wells and pipelines, etc., has been developed. Furthermore, all submerged lands of Texas (4.2 million acres) have been "coded" environmentally by federal and state regulatory agencies to identify and locate environmentally sensitive habitats such as wetlands, submerged grass beds, rookeries and habitats for endangered species, etc. (See selected figures in Appendix I.)

Another important step was taken by the Honorable William P. Clements, Jr., Governor of Texas, in his letter of May 29, 1987, to Mr. Lee M. Thomas, Administrator of the U.S. Environmental Protection Agency, nominating Galveston Bay as an estuary of *national significance* to be preserved for the use and enjoyment of future generations.

Shortly following Governor Clements' action, several environmentally concerned individuals organized the Galveston Bay Foundation. The development of this foundation, with trustees and members from all walks of life, is a monumental step toward ensuring a *public advocate* for the preservation of one of our most valuable national resources — Galveston Bay. Moreover, we believe that the Galveston Bay Foundation will provide the grass roots impetus for the establishment of a statutory *Coastal Zone Management Program* for Texas.

Geology, Climate and Water Circulation of the Galveston Bay System

E.G. Wermund, Robert A. Morton, Gary Powell[1]

Abstract

E.G. WERMUND—The geology of the Galveston Bay System reflects its location in one of the world's largest depositional basins, the northwest Gulf Coast Basin, as well as changes in the rates and balance among sea level, sediment influx and basin subsidence. Sedimentary deposits of two ages dominate the surficial geology surrounding the bays. Deposits of the most recent interglacial period of the Pleistocene Epoch include (1) river sands and floodbasin muds of a deltaic plain and (2) sands of a barrier island system. Modern (Holocene) sediments that entrench and overlie the older strata are (1) fine sand and mud in rivers and bayhead deltas; (2) mud in the bays; (3) oyster reefs in the bays; and (4) sand composing the youngest barrier islands. Galveston Bay is extremely shallow (10 to 12 feet deep) compared with its large areal extent of 600 square miles. Sediment samples, collected a mile apart, are mud in most of the bays; samples coarsen shoreward where sand and reworked shell (gravel) dominate. Geochemical analyses of sediment samples indicate that abnormally high concentrations of barium, boron, chromium, copper, lead, nickel and zinc are products of anthropogenic activities and pollutants.

The Galveston Bay System has a subhumid, subtropical climate; mean summer high temperatures are in the upper 80s (°F), and mean winter low temperatures are in the mid 40s (°F). Mean annual rainfall and surface-water evaporation are approximately 50 inches. Summer winds are dominantly moderate and southerly; winter brings frequent aperiodic strong north winds. Droughts and hurricanes are frequent. Bay circulation is controlled by balances among freshwater influx, tides and storm winds. The Trinity and San Jacinto River Basins provide more than 88 percent of the freshwater inflow to the bays. Bay tides are diurnal in a 14-day cycle, and maximum tidal range is about 2 feet. Hurricane landings may raise the bay level to 15 feet, whereas strong north winds may locally lower bay level about 2 feet.

Principal geologic processes currently altering the Galveston Bay System include (1) a relative sea level rise (about 2 feet in this century) and subsidence (nearly 10 feet at Johnson Space Center) in response to withdrawal of subsurface water, oil and gas; (2) active faulting; and (3) coastal erosion and deposition. Between 1850 and 1982 bay shorelines eroded at an average rate of 2.2 feet per year; before 1930 the erosion rate was 1.8 feet per year, whereas the post-1930 rate was 2.4 feet per year.

Human activities commonly overprint normal natural processes and effect a loss of natural resources. Models of circulation, salinity and nutrients developed by the Texas Water Development Board indicate potential management problems. Further documentation and regular, selective

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[1]E.G. Wermund and R.A. Morton represent the Bureau of Economic Geology, The University of Texas at Austin; Gary Powell, the Texas Water Development Board.

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process monitoring are needed for future holistic management of the Galveston Bay System to be successful.

Introduction

The State-owned submerged lands of Texas include about 1.4 million acres of the inner continental shelf extending about 10.3 miles offshore in the Gulf of Mexico and 1.5 million acres of bays, estuaries and lagoons. Peripheral to these inland bay waters are about 1.1 million acres of marshes and other wetlands.

The Galveston Bay System is one of seven major bays and estuaries along the Texas coast. It contains four major related bays (Figure 1.1); the center of the system is located at approximately 29 30' N and 94 42' W. The two principal water bodies are Galveston Bay at the outflow of the San Jacinto River and Trinity Bay at the outflow of the Trinity River. Buffalo Bayou, a tributary of the San Jacinto River, and Clear Creek have moderate-sized drainage basins contributing freshwater inflow to Galveston Bay. East Bay lies landward of Bolivar Peninsula and receives minor freshwater inflows from the drainage of Oyster Bayou, a small stream. West Bay is located landward of Galveston Island, a barrier island, and receives minor inflow from Chocolate Bayou. Southwest and landward of Follets Island are Bastrop and Christmas Bays, which are comparatively small and essentially isolated from all water sources except tidal exchange. The Intracoastal Waterway enters East Bay at its easternmost location, traverses the southern limits of the bay system behind the barriers, and exits the system through the westernmost shore of Christmas Bay.

Only two tidal inlets permit significant tidal circulation between the brackish water of the bay system and the marine water of the Gulf of Mexico. Bolivar Roads is the major inlet through which international ships travel to the Port of Houston. San Luis Pass is a minor but important inlet for tidal exchange, and both commercial and sport fishing boats use the inlet daily. Rollover Pass, a manmade cut through Bolivar Peninsula, provides minor tidal circulation at the eastern end of East Bay.

The Galveston Bay System is large, encompassing about 340,000 acres (600 square miles) of areal extent, and has a simple geometry. Except for spoil banks and oyster reefs, the bay floor is generally flat and regular. It is very shallow, having a maximum depth of about 12 feet (Figure 1); Trinity Bay is mostly less than 10 feet deep. East Bay is less than 8 feet deep, and West Bay is less than 6 feet deep. Extreme vertical exaggeration of a bay profile is necessary to illustrate bay geometry and changes in elevation. Gulf Coast bays are all very shallow compared with most bays in the United States.

The terrain about the Galveston Bay System has subdued topography and low relief. The coastal plain slopes gently gulfward less than 1 foot per mile, forming a gentle incline at the land-water contact. Bay shorelines may be marshes or small beaches composed solely of shell, sand or mud, or more commonly a combination of these sediments. Because of the small gradient of the coastal lands, a sea-level rise of a few feet can flood the coastal zone inland for many miles. Along some segments of the bay shore, wave-cut bluffs more than 8 feet high occur locally.

Geology

The geology of the Galveston Bay System and environs strongly reflects a dynamic geologic province. Dynamic in this sense does not mean active seismically (subject to earthquakes) but does denote slow, continuous processes reflecting sedimentation, subsidence, faulting and erosion, as well as catastrophic changes caused by hurricanes.

Geologic Framework

The Galveston Bay System is a small part of the northern Gulf Coast Basin, a large area of sedimentary deposition lying between Mexico and Florida. The basic structural and stratigraphic framework of the basin was established in the late Triassic and Jurassic (1), when the North American plate separated from the African and South American plates. During early rifting, the principal deposits were Triassic red beds. Soon after, the basin became isolated, and water inflow was restricted, resulting in the deposition of thick evaporite sections dominated by salt. A major salt basin underlies the Houston Embayment and is the source of local salt domes that produce salt, sulfur, and oil and gas.

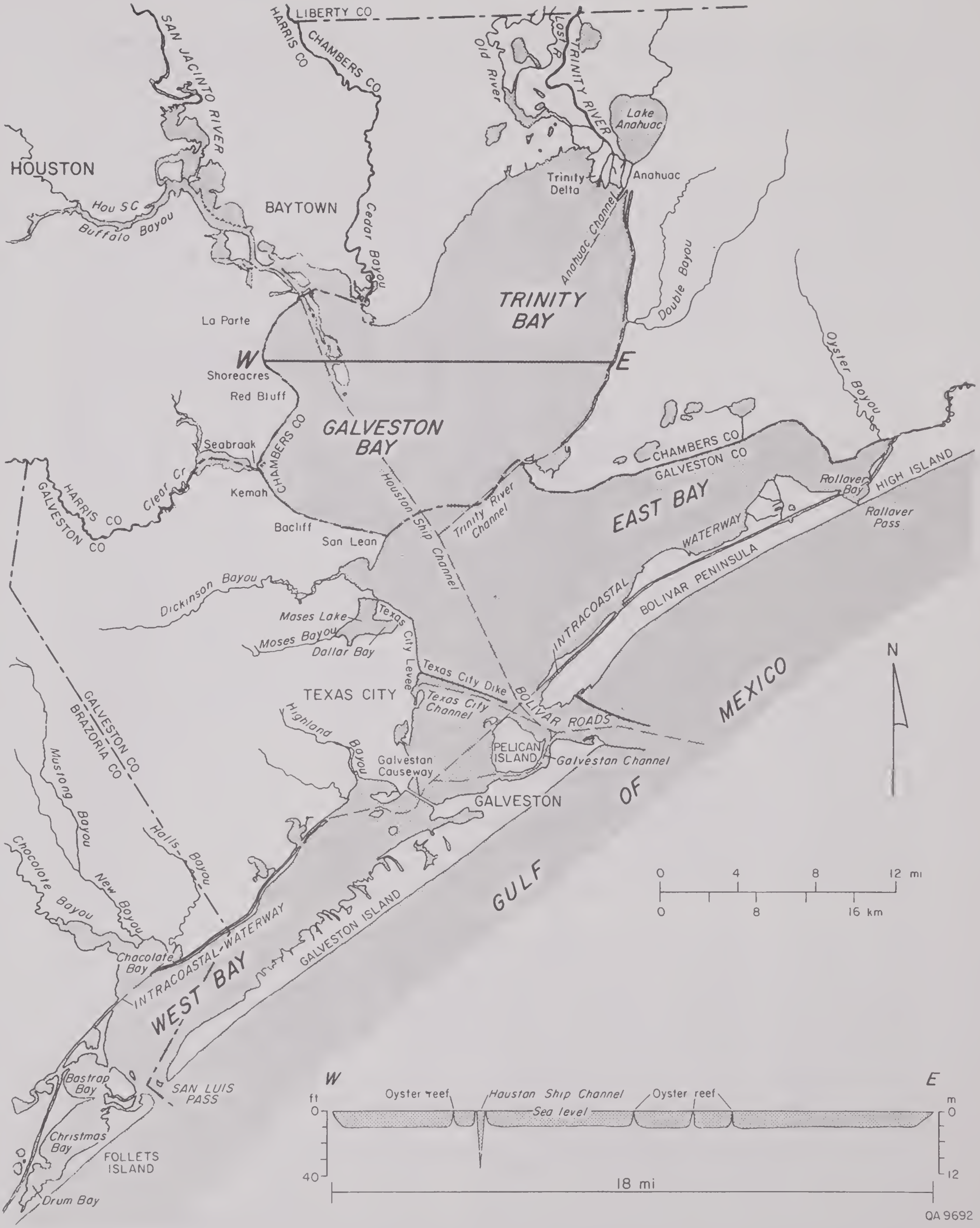


Figure 1.1. Index map of Galveston Bay System locations. Shown are the bays, inlets and streams flowing into the system. The profile illustrating the geometry of the bay bottom has a vertical exaggeration of 132x.

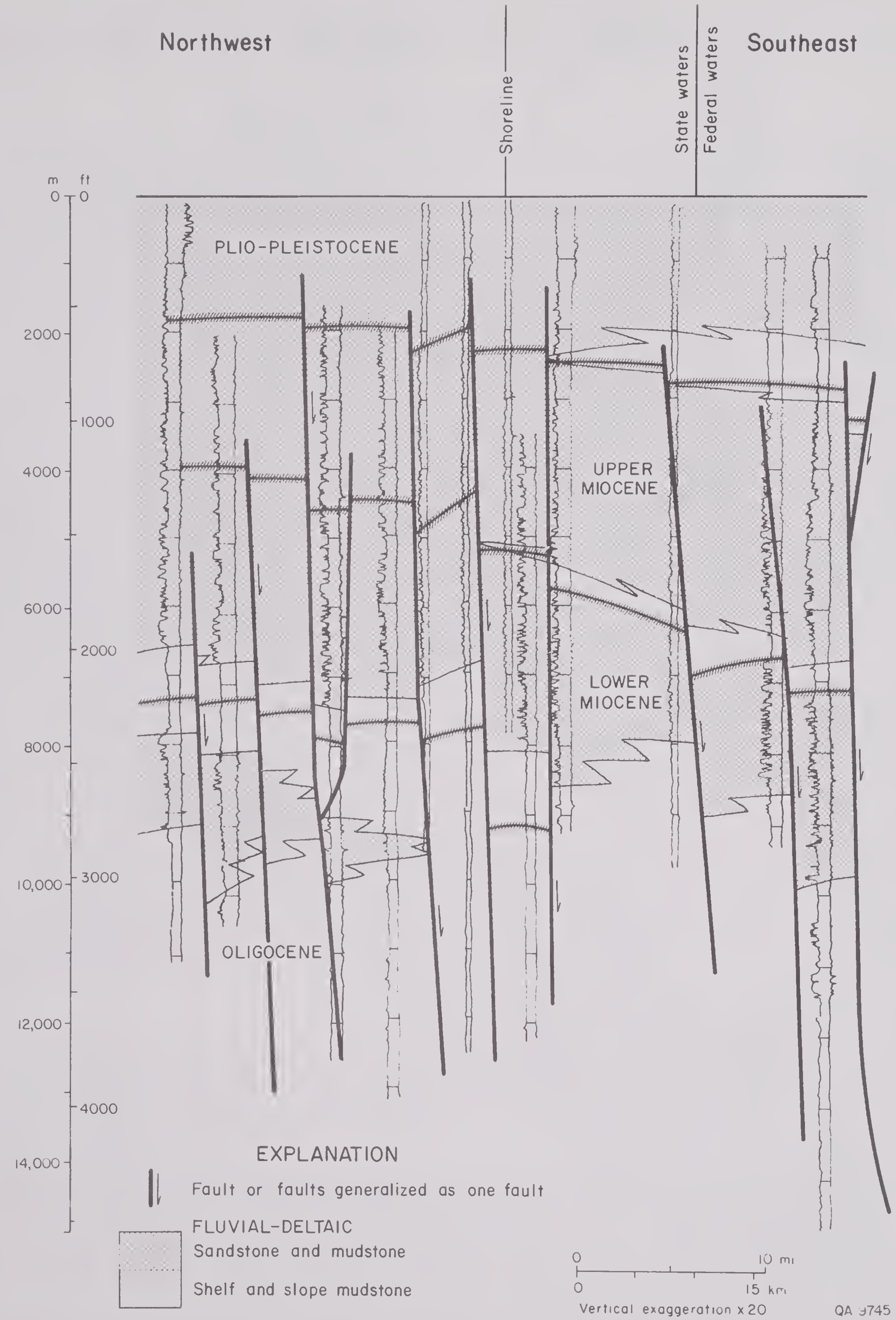


Figure 1.2. Representative cross-section depicting the style of deposition and deep geologic structure in the Galveston Bay system area, modified from Morton and others (1985).

Since salt deposition, the basin has filled principally by prograding sands and muds and, to a lesser degree, by transgressive carbonates. The Triassic to modern sediments vary from less than 3 feet to as much as 50,000 feet in thickness (2). Fluvial and upper deltaic plain sands and muds compose the thinner onshore (updip) part of the sedimentary sequence; deltaic sands and muds and organic-rich slope muds with fine sands and silts form the thickest part of the section. Distal-slope and abyssal muds rapidly thin in the far offshore part of the basin fill.

Overlying the salt, Jurassic and lower Cretaceous continental sediments filled the salt withdrawal basins. Superimposed Cretaceous deposits are dominated by shelf-edge carbonate systems of reefal and bank origins that commonly grade into calcareous, organic, very fine grained slope sediments. Cenozoic facies are dominated by overlapping, progradational sediments similar to those now being deposited by the Mississippi River on its delta and adjacent shelf and slope. The combination of salt gliding under loading, salt diapirism, salt withdrawal from basins and associated faulting, and low-angle, down-to-the-coast growth faulting characterizes the deep geologic structure of the northwestern Gulf Coast Basin. Figure 2 is a representative cross section illustrating the stratigraphy and structure near the study area (3).

The Gulf Coast Basin is a rich petroleum province, and numerous oil and gas fields produce from traps underlying the Galveston Bay System and adjacent onshore properties. A major oil and gas play, the deep-seated Frio salt dome play (4), occurs in an area of deeply buried salt diapirs surrounded by shallow piercement domes that formed contemporaneously with the Frio-age (Oligocene) Houston delta system. Cedar Point and Trinity oil fields underlie the bay and have produced, respectively, 13.2 and 21.2 million barrels of oil. On the west side of Galveston Bay, Clear Lake (22.1 mmbbl), Gillock (24.4 mmbbl), South Gillock (20.7 mmbbl), East Gillock (44.3 mmbbl), and Webster (528.0 mmbbl) are onshore fields producing from the same play. In addition, many other productive fields occur in smaller plays containing sandstone reservoirs formed in progradational sequences, faulted zones and deformed strata surrounding salt diapirs.

Surficial Geology

The surficial deposits surrounding the Galveston Bay System represent only recent geologic history, the final depositional and erosional phases of the Pleistocene ice ages, and the Holocene post-glacial events (5) (Figure 3). The major control effecting most geomorphic features and sedimentary deposits is the recent history of sea-level fluctuations. Sea level was lowered by nearly 450 feet when glaciers advanced to their farthest limits on the northern continents. Then streams like the San Jacinto and Trinity Rivers eroded deep broad valleys entrenched into the land and former continental shelves and deposited their sedimentary loads onto the former shelf and slope. Sea level was highest when the glaciers melted and retreated. A rising sea inundated the entrenched valleys, and the locus where the streams deposited their sediments progressively shifted landward. All the modern sedimentary systems owe their attributes to the most recent sea-level rise following the last major glacial advance in North America. The size and shape of bays, inlets and barrier islands reflects this most recent eustatic cycle.

Two Pleistocene formations, the Beaumont and Deweyville Formations, crop out near Galveston Bay. The Beaumont Formation is composed predominantly of clay, silt and sand where the sediments were deposited in fluvial, delta plain and bay environments. A large river system, having meander channels larger than those of today, transported mainly sand and silt when sea level was lowered during glaciation and while sea level rose during interglacial periods. An extensive Beaumont deltaic plain is composed of sand and silt deposited in the distributary channels and of organic-rich clays and silts deposited in the interdistributary areas. Locally, fine-grained and fossiliferous muds represent former bay deposits. Some Beaumont sediments are composed of mostly fine-grained sand arranged in linear trends parallel to the coast. These linear features are higher in elevation (>8 feet) than surrounding sediments, and they are characterized by pimple mounds and circular depressions. These sand-rich deposits represent a former barrier island much like those of the modern Gulf Coast.

The Deweyville Formation, which is generally younger than the Beaumont Formation, contains coarser grained sediments including gravel. These fluvial-dominated sandy sediments rarely contain clay and silt except in outcrops of backswamp facies. Deweyville exposures, which also exhibit

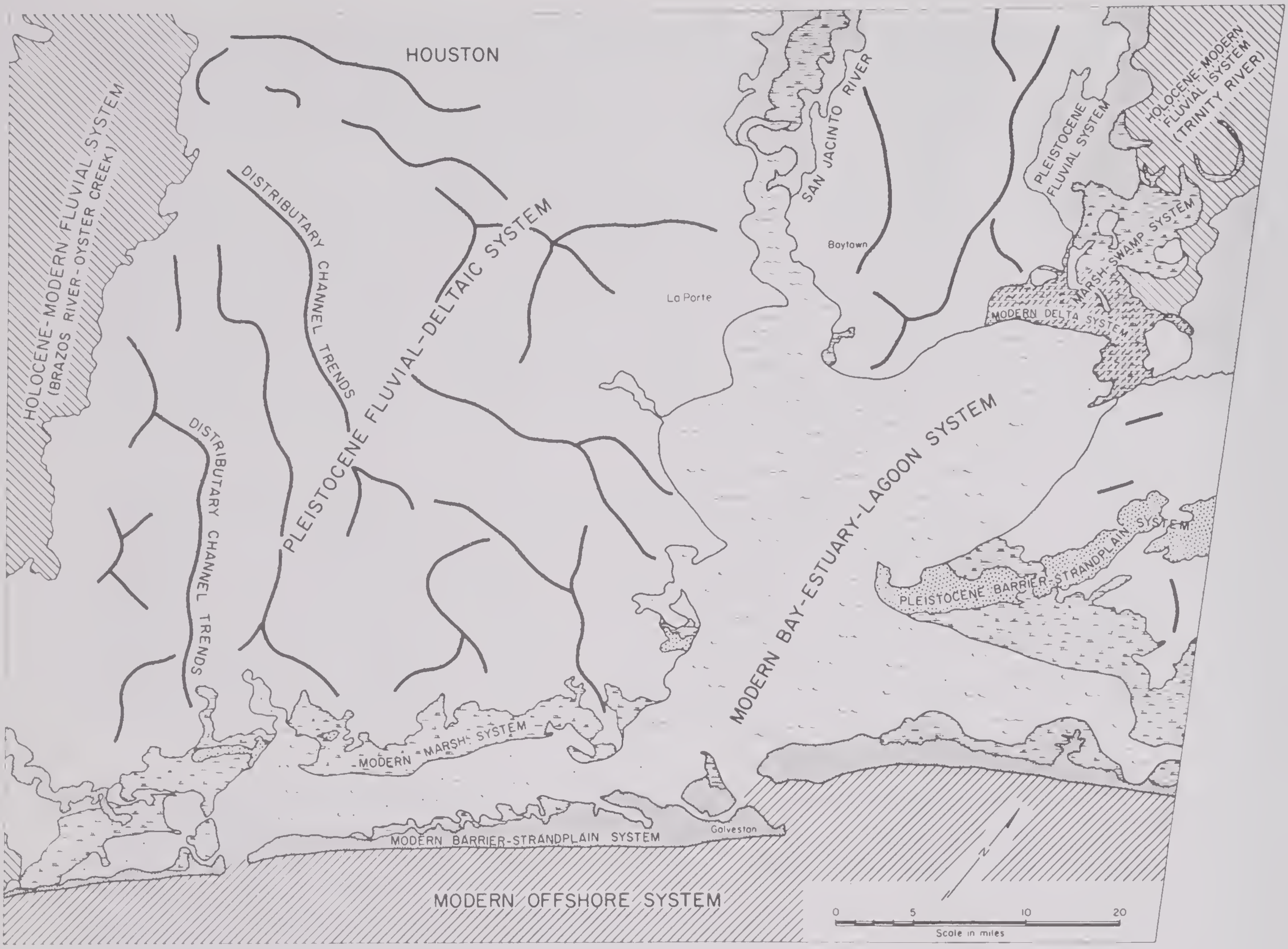


Figure 1.3. Simplified map of Pleistocene and Holocene depositional system of the Galverston area, after Fisher and others, 1972 (5).

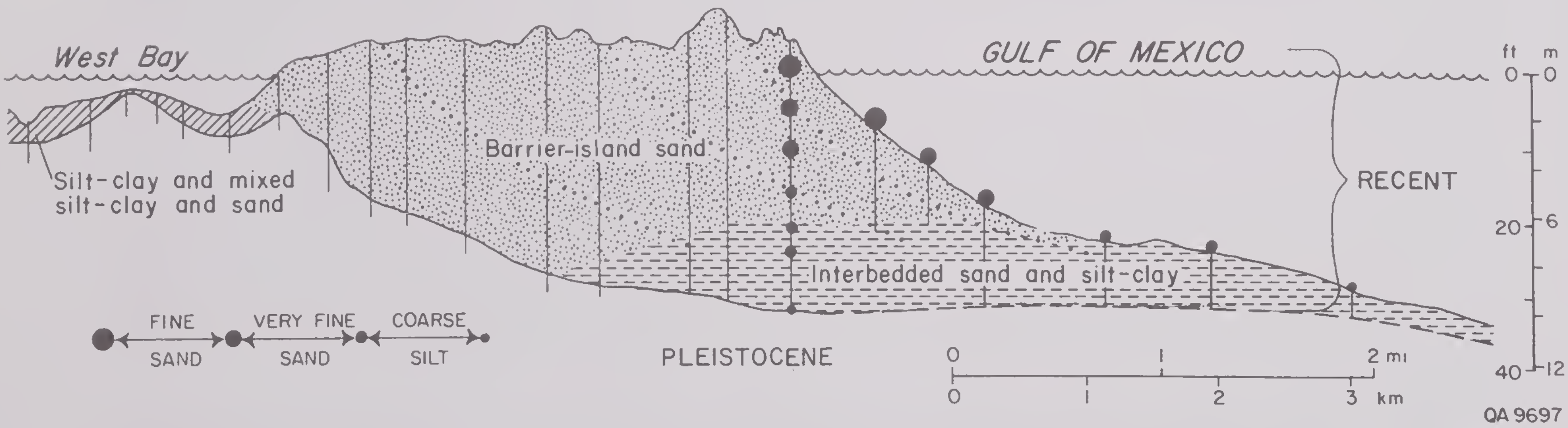


Figure 1.4. Cross-section of Galveston Island showing the grain-size distribution, accretionary ridges and bedding planes (dotted lines), after Bernard and others, 1970 (6).

meander scars that are larger than those of modern rivers, crop out in terraces above the Trinity and San Jacinto floodplains. Although the Pleistocene streams appear to have been larger, the geologic processes forming Beaumont and Deweyville deposits resemble those active today in the vicinity of the Galveston Bay System.

The Holocene units on the geologic map (5) are like the Pleistocene deposits described above, except for one anthropogenic unit, fill and spoil. These man-made deposits, readily seen at a scale of 1:250,000, occur along Buffalo Bayou and the Houston Ship Channel, formerly in the San Jacinto River floodplain, in the Texas City Dike, in much of Pelican Island, and behind the northeast end of Galveston Island. Very fine sand, silt and clay compose the Quaternary alluvium in the valleys of the Trinity and San Jacinto Rivers and the bayhead deltas where the rivers empty into the bays. Slightly finer sediments dominate minor stream valleys, because these streams derive their load from the surrounding Pleistocene sediments. Fine sands containing some shell are the principal sediments composing two modern barrier islands, Galveston Island and Bolivar Peninsula.

Aerial photographs, cores and radiocarbon dates permit reconstruction of the geologic history of Galveston Island (6). Linear ridges and swales nearly parallel to the present shoreline are clear evidence of the seaward accretion. The barrier is composed of fine sand at the surface, which becomes finer both deeper and seaward, and beds dipping seaward slope increasingly less at depth (Figure 4). Maximum thickness of the well-sorted, relatively pure barrier sand is about 30 feet. The basal strata are approximately 5,300 years old. Galveston Island formed a narrow sand bar and enlarged with the seaward accretion of offlapping fine sand (Figure 4). Because of the thickness of the deposit, the attitude of the bedding and bulwarking of underlying stiff Pleistocene clays, a relatively stable barrier island results, in contrast to the less stable barriers of the east coast of the United States.

Bay Geology

Researchers at the Texas Bureau of Economic Geology (7) described the geology of the bay floor using samples collected on 1-mile centers in the bays and about 1 mile apart in tidally affected streams. Sampled sediments came from a thin veneer overlying the coarser Pleistocene/Holocene sediments that filled entrenched valleys during the sea-level rise. Samples were classified on the basis of relative percentages of gravel (shell and rare rock fragments), sand and mud (silt and clay). Mud composes the largest expanses of the bay, especially in the deep bay centers (Figure 5). Gravel (shell) is more common in very shallow water and adjacent to shorelines. Gravel (shell) and sand occur only in the highest energy environments; both are more abundant near the shorelines and in shallow water affected by storm waves. Oyster reefs form the only other sediment type in the bays. Because of their high calcium content, they are comparable to limestones in older rocks.

In addition to measuring the textural characteristics of the bay sediments, researchers conducted multi-element chemical analyses on most samples (Table 1). Total organic carbon was measured separately. Thirty major and trace elements were analyzed spectrographically, of which 11 elements were reported. These selected metals—barium, boron, calcium, chromium, copper, iron, lead, manganese, nickel, strontium and zinc—are useful for understanding the geology of the bay and for detecting anthropogenic impacts on the bay. Largest boron concentrations (+148 ppm) occur in bay muds having the highest total organic carbon. Manganese also associates with greater organic carbon concentrations in fine-grained sediments (400-1,800 ppm). Highest strontium concentrations (>1,000 ppm) are in oyster reefs. Because metals are frequently associated with industrial pollution, those are reported separately in Table 1 with natural levels versus contaminated sediment values.

Bay sediments have probably been affected by salt diapirism and/or faulting, but satisfactory data are unavailable; thus, the effects of these processes on bay geology cannot be assessed.

Climate

The Galveston Bay System lies within the warm part of the temperate zone of the Northern Hemisphere. Texas climate is controlled by (1) latitude, (2) proximity to the Gulf of Mexico, (3) winds blowing gulfward from Pacific and Arctic frontal systems, (4) decreasing elevation north and west to south in Texas, and (5) a position west of the Bermuda high-pressure cell (8). The Galveston area has a modified maritime climate controlled by the Gulf of Mexico and is classified as subtropical-subhumid.

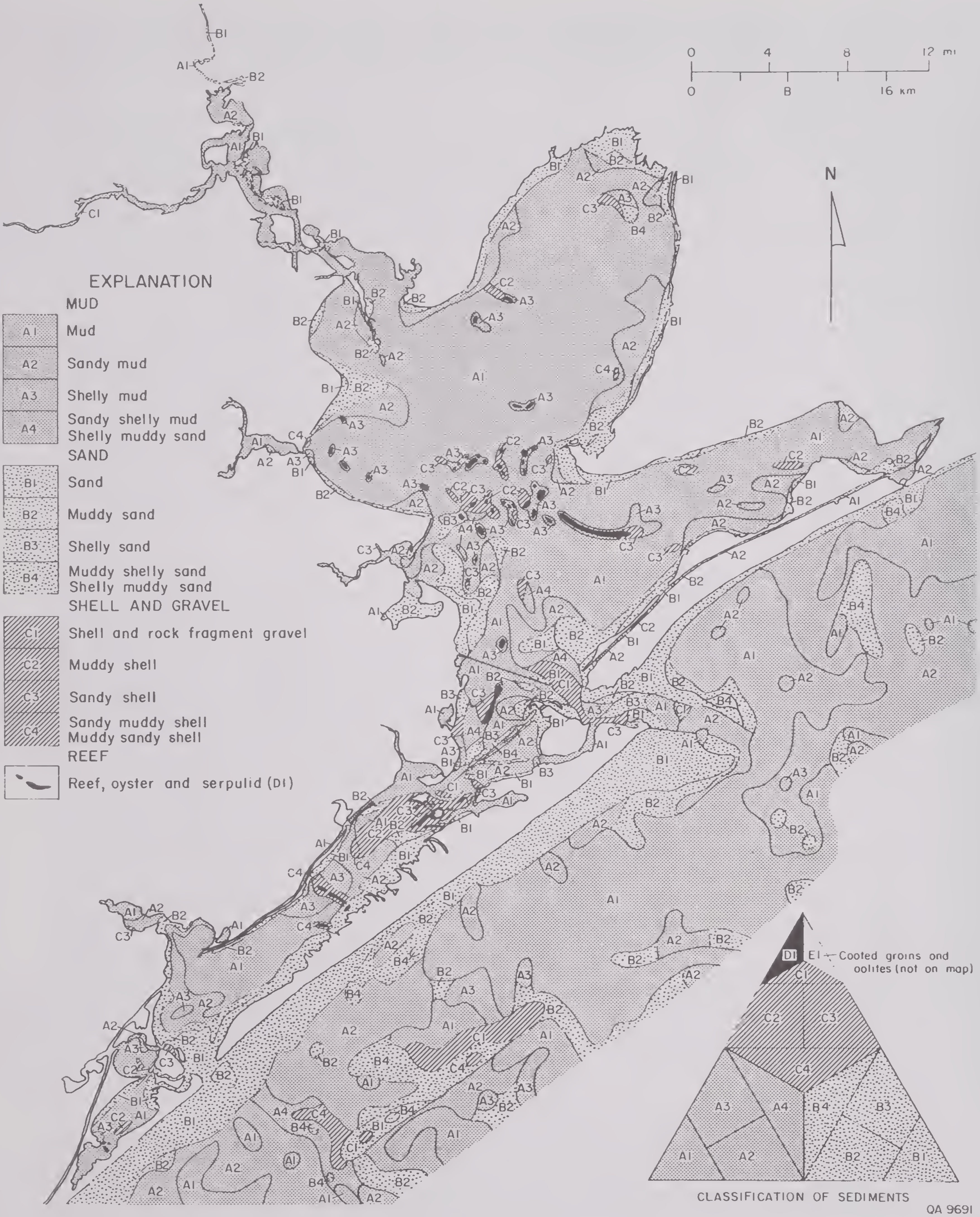


Figure 1.5. Geologic map of Galveston Bay sediments, after McGowen and Morton, 1979 (7), and White and others, 1985 (7).

Table 1.1. Comparison of Trace Element Concentrations in Sediments (Mud) of the Galveston-Houston Area with Those in Uncontaminated Sediments (Baseline Levels) and Contaminated Estuarine Sediments along the Texas Coast. Values in PartsPer Million.

	Galveston-Houston Area[1]				Baseline Levels					Contaminated Sediments
	Bay sediments (muds)		Shelf sediments (muds)							
	mean**	high***	mean	high***	Shale	Nearshore sediment	Clays and shales	15th-16th century sediment in Rhine estuary	Modern marine argillaceous sediment	Example of high estuarine sediment value, Texas coast
Barium	413	1,600	538	1,300	580	750	800			910
Boron	79	148	70	88	100		100		90	
Chromium	55	120 150*	45	98	90	100	100	63	6-72	134
Copper	28	130 160*	18	34	45	48	57	21	37	1,510
Iron	26,000	43,000 62,000*	30,000	37,000	47,200		33,300			
Lead	34	140 260*	19	24	20	20	20	31	21	340
Manganese	400	1,400 1,800*	783	1,300	850	850	670			1,400
Nickel	26	113	28	34	68	55	95	33	40	160
Zinc	89	275 590*	53	110	95	95	80	93		4,900

[1]Appendix B; muds = sediments >75% mud (<63 microns in particle size)
**Excludes Buffalo Bayou/Houston Ship Channel
***Highest recorded value (not limited to muds)

Source: White and others, 1985 (7).

Table 1.2. Representative Temperatures at Galveston, 1951-1980.

Measurement	Date	Temperature (°F)
Average monthly low temperature	February	49
Average monthly low temperature	July	78
Average monthly high temperature	February	62
Average monthly high temperature	July	88

Source: Compiled from Larkin and Bomar, 1983 (8); Riggio and others, 1987 (9), and Schexnayder, 1987 (10).

According to a classification developed principally on annual rainfall, the study area lies in an "Upper Coast" climate (9). Based on 1951-1980 records for this climatic division, the average annual precipitation at Galveston is about 44 inches. Most precipitation at this location occurs in early fall and late spring and coincides with the passage of frontal systems. Average annual precipitation is nearly balanced by the average annual gross lake evaporation rate, which is 45 inches. Mean annual sunshine, expressed as a percent of possible sunshine, is about 60 percent.

Representative winter and summer temperatures at Galveston are shown in Table 2 (8). Because the Gulf of Mexico moderates the temperature in all seasons, the temperature inland has greater extremes. For example, the average monthly low temperature in February in Houston is nearly 44°F (49°F in Galveston); the average monthly high temperature in July in Houston approaches 94°F (88°F in Galveston). Average winters in Galveston have only four days with a temperature below freezing and summers have an average of 13 days above 90°F. The lowest recorded temperature is 8°F in 1899; the highest temperature is 101°F in 1932. At the Galveston Airport, mean relative humidity is 83 percent at 6 a.m. and about 90 percent at 6 p.m. (10). Winters are mild, and summers are warm and humid; there is less daily temperature variation in summer. The bay area averages 335 growing days for local agriculture.

The predominant winds for the year blow from the southeast (8). However, wind patterns for the summer are very different from winds patterns for the winter (Figure 6). In June through August, winds have mainly southern and eastern components. From December through February, north winds blowing in excess of 10 knots dominate, and alternate with lighter south winds. During "blue northers," winds up to 40 knots increase wave height, push several feet of water out of the bays, and tilt the level of the bay surface. Then oyster reefs commonly stand well above the water surface.

The Texas climate has two phenomena that greatly skew average and mean climatic data—droughts and hurricanes. A serious drought has harmed some region in Texas each decade of the 20th Century: During 1950-1956 a major drought plagued every sector of Texas. A drought in the river basins supplying fresh water to the Galveston Bay System is potentially more devastating than drought within the bay system. The Texas Water Commission made a special study of droughts (9) between 1931 and 1985 to plan water needs better. A map (Figure 7) of the frequency of occurrence of six-month drought in Texas, 1931-1985, shows the basins to be less affected than most of Texas. However, 22 such droughts affected the West Fork of the Trinity River. If severe to extreme droughts are considered, only six to eight severe droughts occurred here, compared with more than 12 droughts elsewhere (including Laguna Madre).

Tropical storms or hurricanes strike the Texas coastline with a frequency of 0.67 storms per year (11). The amount of geomorphic adjustment or damage caused by these storms depends upon the approach speed, wind velocity, barometric pressure at the storm's eye, storm surge height, wave height, direction of approach to the coast, and total rainfall. Recorded maxima of these parameters are, respectively, 17 mph for an unnamed storm at Port O'Connor in 1929; 140 mph for Hurricane Beulah at Brownsville in 1967; 27.49 inches (lowest) at Port O'Connor for Hurricane Carla in 1961; 22

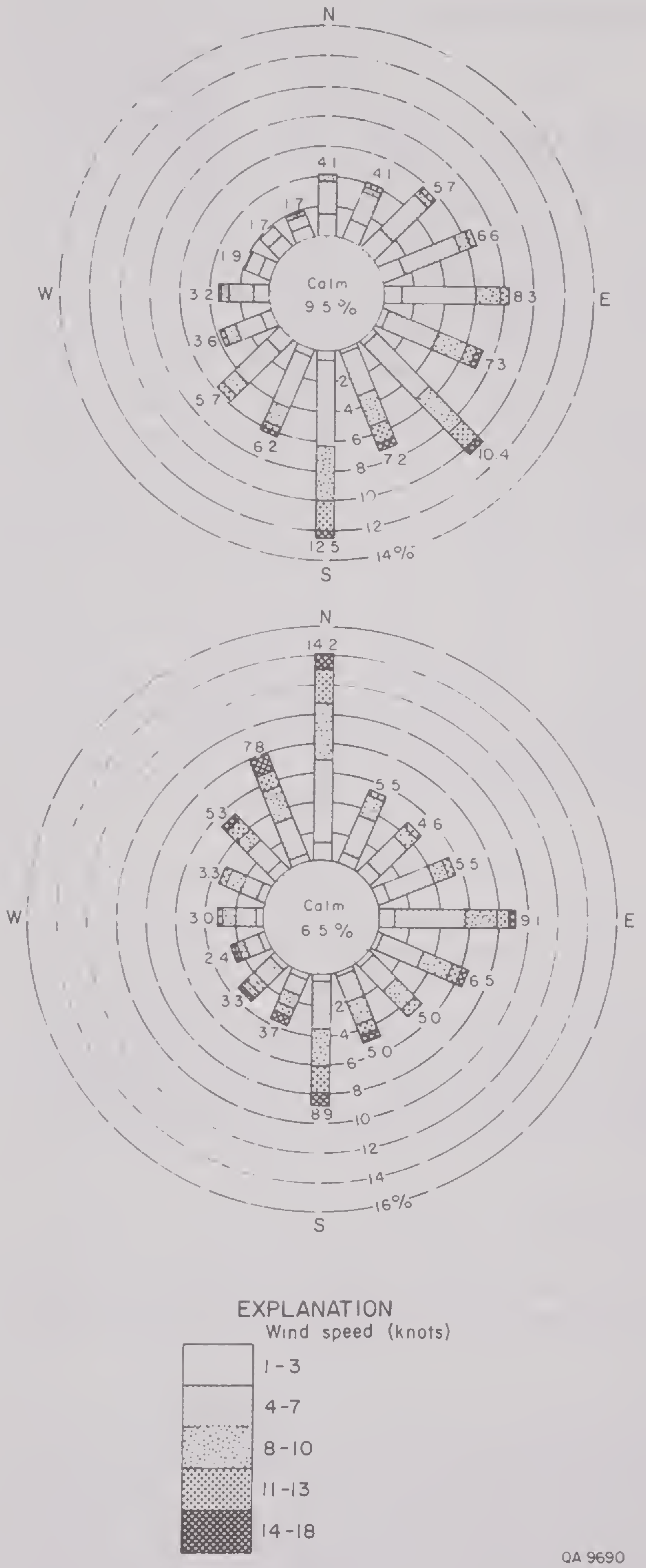


Figure 1.6. Wind rose for summer (upper diagram) and winter (lower diagram) winds at Houston Intercontinental Airport, 1971-1980. Summer is June-August; winter is December-February, after Larken and Bomar (1983). Length of the bar in a rose indicates the percent of days per three months the wind blows from a given azimuth.

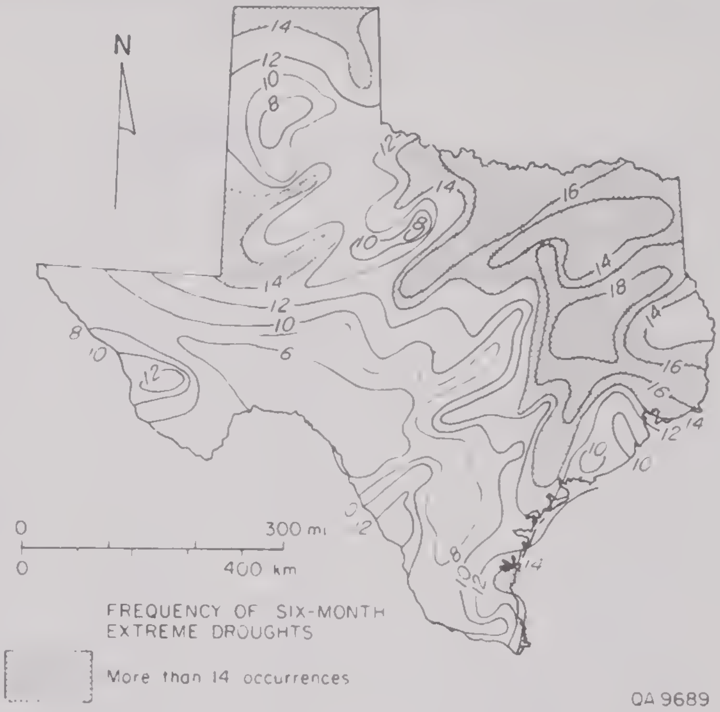


Figure 1.7. Frequency of occurrence of six-month droughts in Texas, after Riggio and others, 1987 (9).

Table 1.3. Tidal Ranges in the Galveston Bay System for 1988.

Location	Position N lat.	Position W long.	Time High H.M.[1]	Time Low H.M.[1]	Height High (ft)	Height Low (ft)	Ranges Mean diurnal (ft)[2]	Mean Tide Level (ft)[3]
Galveston Channel	29°19'	94°48'	—	—	—	—	1.4	0.7
Texas City	29°23'	94°53'	+0033	+0041	0.00	0.00	1.4	0.7
Clear Lake	29°34'	95°04'	+0605	+0640	0.64	0.64	0.9	0.4
Morgan Point	29°41'	94°59'	+1021	+0519	0.71	0.71	1.0	0.5
Trinity Bay	29°44'	94°42'	+1039	+0515	0.71	0.71	1.0	0.5
East Bay	29°31'	94°29'	+0316	+0418	0.86	0.86	1.2	0.6
Christmas Bay	29°05'	95°10'	+0232	+0231	0.64	0.64	0.9	0.4
San Luis Pass	29°05'	95°07'	-0009	-0009	0.86	0.86	1.2	0.6
Gulf of Mexico (Galveston area)	29°17'	94°47'	-0106	-0106	1.50	1.50	2.1	1.1

[1]H.M. = Hours and minutes to be added to or subtracted from the time of high or low water at a reference station. + = tide at subordinate station is later than at the reference station and should be added. - = tide is earlier and should be subtracted.

[2]Mean diurnal range is the difference in height between mean higher high water and mean lower low water.

[3]Mean tide level is a plane midway between mean low water and mean high water.

Source: U.S. Department of Commerce tide tables, 1987.

feet at Port Lavaca for Hurricane Carla in 1961; 40 feet at sea for Hurricane Carla in 1961; and 30 inches near Brownsville for four or five days during Hurricane Beulah in 1967. Saltwater flooding from Carla extended as much as 15 miles inland in the Galveston-Houston vicinity. Galveston has been the principal landfall site of four hurricanes since 1900; Hurricane Alicia in 1983 was the most recent (12).

Bay Circulation

Principal mechanisms that drive the circulation in the Galveston Bay System are prevailing winds, tides and freshwater inflow. Prevailing winds and normative speeds are documented above (Figure 6); salinity and nutrient gradients may be modeled, given a holistic understanding of the bay circulation system.

Tides

Tides are an important driving force in all bay systems; in the Galveston Bay System, tides are relatively weak (13). Tides cycle every 14 days. There are 14 days of one high and low tide followed by 14 days of two high tides and two low tides of different magnitudes. The tidal station inside the Galveston Channel records a mean annual tidal range of 1.4 feet, whereas the mean annual tidal range for the Gulf of Mexico at Galveston Pier is 2.1 feet (Table 3). The maximum tidal range in the bay for a 1988 spring tide is 2.4 feet. The tidal range decreases northward into upper Galveston and Trinity Bays, eastward in East Bay, and westward in West Bay as circulation becomes increasingly distant from the inlets. However, because of the location and orientation of the Intracoastal Waterway, tides appear tohave higher velocities than expected in East and West Bays.

Approximately 80 percent of the tidal exchange between the Gulf of Mexico and the Galveston Bay System occurs through Bolivar Roads (13). Less than 20 percent of the tidal exchange occurs

Roads. The tide tables illustrate the slow progression of the tides between the inlets and the upper bay tidal stations (Table 3).

Freshwater Inflow

Not every stream entering the bays has a stream gauge; consequently, Texas water agencies group the streams into basins in measuring and calculating freshwater inflow (15). Inflow into the Galveston Bay System is gauged for the Trinity and San Jacinto Rivers. Inflow is calculated for the minor basins composed of small streams; these basins are the San Jacinto-Brazos Coastal Basin, the San Jacinto-Trinity Coastal Basin, and the Trinity-Nueces Coastal Basin. From calculations for the years 1941-1976, the average annual freshwater inflow to the Galveston Bay System from the two principal basins and three lesser basins was 11,340,000 acre-foot. For the same period, the maximum annual freshwater flow was 23,696,000 acre-foot in 1973, and the minimum annual inflow was 2,913,000 acre-foot in 1956, near the end of the worst Texas drought of this century. For the same years the freshwater inflow balanced against evaporation losses were, respectively, 22,290,,000 and 1,321,000 acre-foot.

Measurements of the average annual inflow and average monthly inflow of the major contributing stream, the Trinity River, show similar patterns for the years 1941-1976. Until 1970 there was a large difference in the fluctuation of flood stage and low stage; thereafter, the difference between high and low stages has been small. However, for the same time period the mean annual inflow equals about the same amount. The alteration of the inflow pattern correlates with the increase in upstream dams after the 1950 drought years.

On the basis of exceedance frequencies for monthly freshwater inflows between 1941 and 1976 (16), it was calculated that the Trinity River Basin supplies more than 70 percent of inflow during the wet months of December through June. The San Jacinto River Basin supplies about 18 percent and the San Jacinto-Brazos Coastal Basin supplies less than 2 percent. Inflows from the coastal basins that have ungauged streams are roughly calculated from the size, slopes and stream gradients of small streams.

Salinities and Nutrients

Circulation in the Galveston Bay System reflects bathymetry of the bays and tidal inlets, location and amounts of freshwater inflow, location and amounts of saltwater inflow, velocity and orientation of tides, bottom friction, wind speed and direction, rainfall history, and surface evaporation. Most of these variables are well known, as we described previously in this paper. However, because no current meters have been set in the major inlets for a long term, only brief temporal measurements of exchange in the inlets are available. In order to understand salinity changes and nutrient processes in Galveston Bay, the Texas Water Development Board has modeled tidal circulation, salinity changes and nutrient processes (16). The model simultaneously solves multiple tidal hydrodynamic equations over a rectangular grid of cells in a discrete fashion.

Monthly vector plots of the net flow through each computational cell show similar circulation patterns for groups of months (16). In March, August (Figure 8) and October, the most evident circulation pattern in the Galveston Bay System was a northwesterly directed current in the Houston Ship Channel and a clockwise circulation in Trinity Bay moving along the eastern shore. The current in West Bay was predominantly directed in a northeasterly direction from San Luis Pass to the Galveston Ship Channel. In January, February, July, September, November and December, the current in the Galveston Ship Channel was directed southeastward, and the dominant flow in Trinity Bay rotated counterclockwise along the northwestern shore. An internal current rotated counterclockwise in West Bay with the net water movement from Bolivar Roads through the Galveston Ship Channel and through San Luis Pass via West Bay into the Gulf of Mexico. In April, May and June, months of largest freshwater inflow, a very strong southeasterly current prevails in the Houston Ship Channel. Trinity Bay flow is counterclockwise in April and May, but clockwise in June, and northeasterly moving currents dominate flow in West Bay during the same months.

Simulated salinity gradients, calculated from the model, also display seasonality. The lowest salinities occur in June, whereas the highest salinities appear in August (Figure 8). In the spring and early summer (March, April, May and June) salinity is generally less than 5 ppt in Trinity Bay, 10 ppt in Galveston Bay, 25 ppt at Bolivar Roads, 20 to 25 ppt in West Bay, and 10 to 15 ppt in East Bay. During these four months an intrusion of salt water is evident along and beside the Houston Ship Channel.

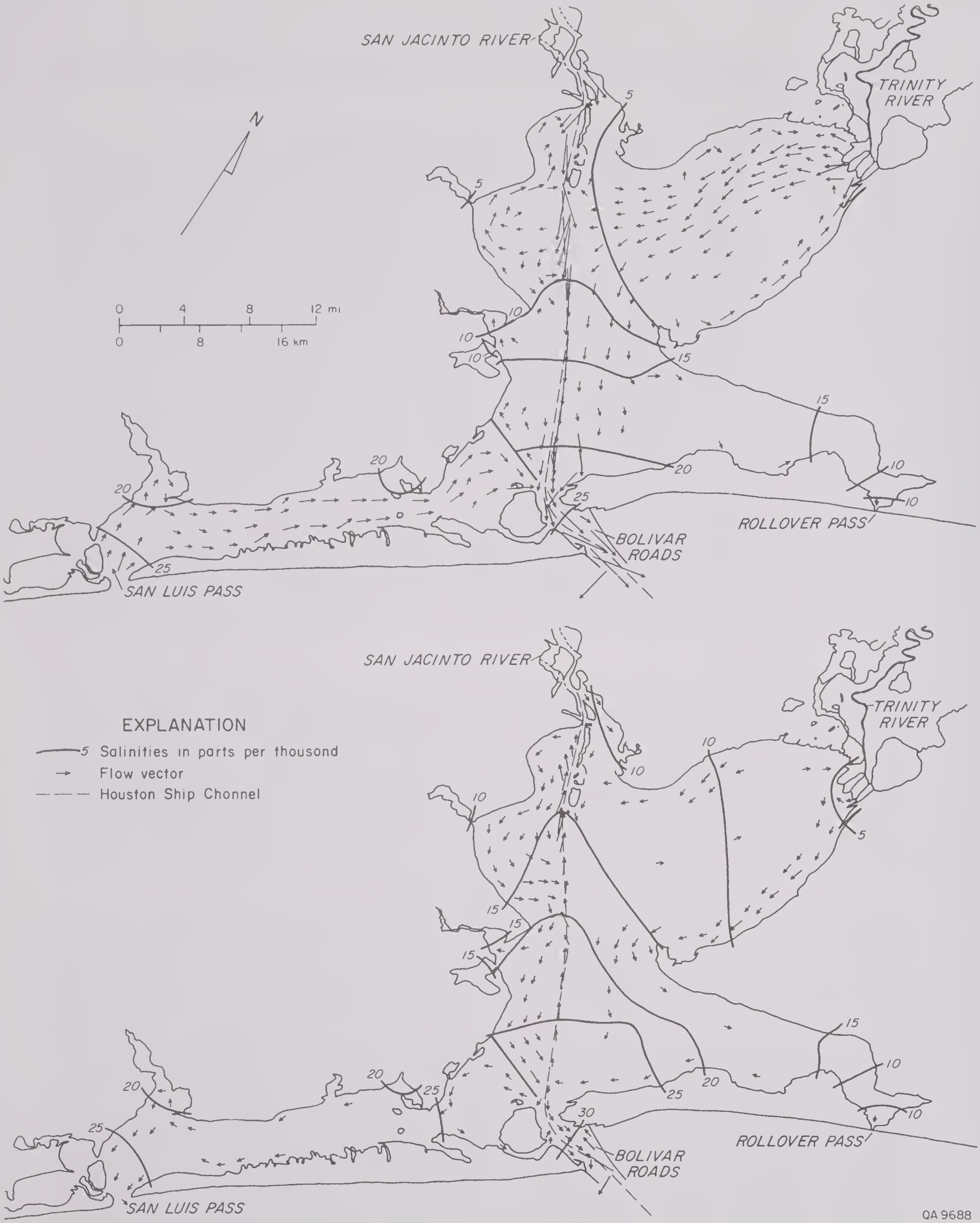


Figure 1.8. Simulated salinities in the Galveston Bay System, 1941-1976, under the influence of freshwater inflows for May (freshest) and August (most saline), and average monthly circulation patterns for same months, after Texas Water Development Board, 1982 (16). Top diagram is May; lower diagram is August.

For the remainder of the year, the salinities are generally near 10 ppt in much of Trinity Bay, 10 ppt in upper Galveston Bay to 25 ppt near Bolivar Roads, less than 20 to 25 ppt west to east in West Bay, and 10 to 25 ppt east to west in East Bay.

Nutrient gradients in the Galveston Bay System reflect the richer nutrient composition of the contributory freshwater streams and the nutrient-poor saline waters of the Gulf of Mexico (17). In addition, nutrients are generated and contributed by biochemical cycling in bayhead deltas as well as by marshes and nonpoint sources from agriculture. Magnitudes of freshwater inflows, winds, currents and biological activity complicate understanding the effects of nutrient processes at any one time.

Measurements of water quality in the Trinity River upstream of the delta indicate that mean monthly organic nitrogen varies from 0.39 mg/L to 0.79 mg/L(16). Concentrations in the upper part of the Houston Ship Channel/Buffalo Bayou area, in contrast, ranged from 1.0 mg/L to greater than 2.0 mg/L. Maps displaying average organic nitrogen from 1968 to 1987 show a gradient of concentration from greater than 0.5 mg/L in the upper reaches of the Houston Ship Channel to 0.5 mg/L to 0.2 mg/L down-channel and along the northwestern shore of Trinity Bay. Concentrations continue declining gulfward by several orders of magnitude, and there is a plume of 0.2 mg/L to 0.1 mg/L organic nitrogen flowing through Bolivar Roads. Both West Bay and East Bay have negligible organic nitrogen concentrations of less than 0.1 mg/L.

In the same study period, average phosphate concentrations are more than 0.5 mg/L in northwestern Trinity Bay, in the upper Houston Ship Channel, and in western Galveston Bay. Considerable dilution is evident near the Trinity River. West Bay has extremely low phosphate content, as does East Bay near Rollover Pass.

The north-to-south nutrient gradients in the Galveston Bay System, encompassing more than two orders of magnitude and the plumes flowing out Bolivar Roads, deserve continued monitoring, as do seasonal concentrations approaching eutrophism.

Active Processes

The interconnected active processes of today are the same as those that occurred in past geologic time and that first formed the Galveston Bay System. Continuously changing magnitudes and rates of sediment influx, sea-level change (Figure 9), subsidence, faulting, and erosion and accretion are demonstrated by gains and losses of land, bay or Gulf. In contrast to active geologic processes, human activities rapidly alter or overwhelm the short-term effectiveness of some of the natural active processes in sculpting the bay system.

Sediment Influx, Natural Subsidence and Sea-Level Change

Sediment influx is significant where streams enter the bay system. Continuous sedimentation, in the absence of sea-level rise and subsidence, causes shoreline accretion and provides both stable land and nutrients for new marsh growth. Decreased rate of sediment influx with a concomitant rise of sea level or increased subsidence produces shoreline erosion and removes marsh.

Records from the Trinity River near the delta from 1935 to 1980 show a continuous decline in the suspended sediment load beginning in 1950, coincident with the increased dammed reservoir capacity (17). The upstream reservoirs trap not only bed load but also a considerable fraction of the suspended load of streams. For the interval (1904-1980), combined tidal records at Galveston (18) show a relative sea-level rise of nearly 1.5 feet (Figure 9).

Recently the bayhead deltas of the principal streams feeding Galveston Bay have begun to lose land and elevation. The loss of land between 1956 and 1979 reflects decreased influx of sediment and natural subsidence related to compaction of deltaic sediments; a rise of sea level, although possibly involved, is not documented. Figure 9 illustrates the loss of fluvial woodlands, swamps and marshes in the San Jacinto delta area (7).

As noted previously, subsidence is a continuing natural process in which thick sedimentary deposits compact over long periods of time. An overprint of additional subsidence, in excess of 10 feet at some locations in the Houston metropolitan area, has occurred since 1906 as a result of withdrawal of subsurface fluids. A large bowl-shaped area more than 80 miles in diameter has subsided principally because of groundwater removal (19). Subsidence along the bay at Clear Lake Bayou near

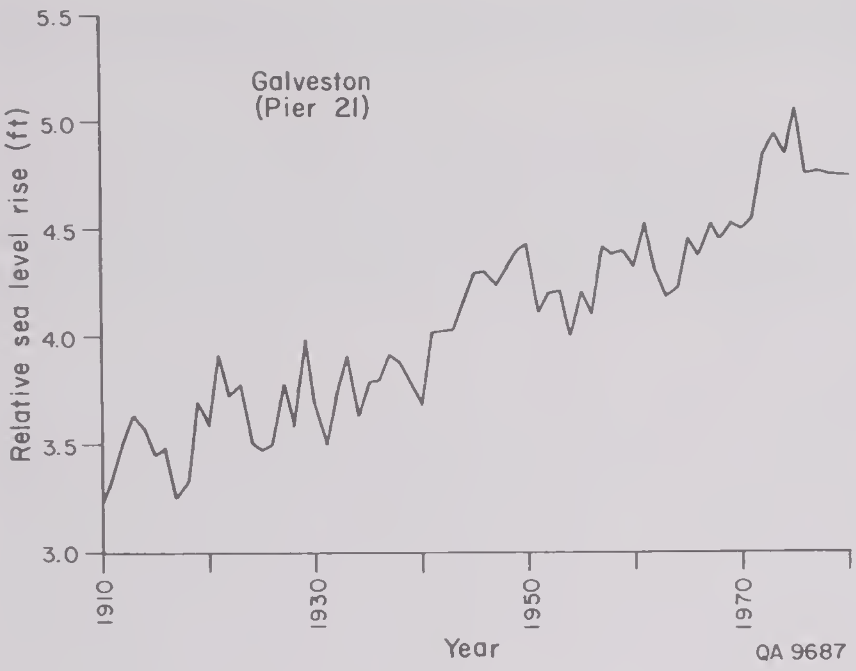


Figure 1.9. Relative sea level measured at Pier 21 in Galveston, 1910 to 1980.

principally because of groundwater removal (19). Subsidence along the bay at Clear Lake Bayou near the NASA Space Center measures 5.5 feet. A housing subdivision near Baytown is now submerged beneath several feet of bay water, thus contributing the complex chemicals of developed properties and roads to the bay system. More than 30 percent of the park land (130 acres) subsided into the bay at the San Jacinto Battleground. Recently, the subsidence rate in these areas has decreased, in part related to better management of groundwater pumping regulated by the Harris County Subsidence District.

Not all man-induced subsidence relates to ground-water pumpage; some subsidence clearly relates to oil and gas production, especially as production includes reservoir water as well as oil and gas. In the Galveston Bay area a larger net subsidence represents the integration of pumping ground water and petroleum. The two localities of maximum subsidence, Pasadena and Baytown, probably experienced exploitation of both fluids.

Faults

Faults related to the original deposition of sediments and to subsequent formation of salt domes persist as planes of weakness and remain active today on the land surface (19) and on the seafloor of the bays and Gulf (7). Depositional and compactional faults generally form arcuate trends, more than 20 miles long, subparallel to the Gulf shoreline. Faults associated with salt diapirs typically form a peripheral complex of horsts and grabens constructed of short straight faults with a radial pattern. Natural escarpments at the surface, which reflect the vertical offsets of the faults, are generally less than 3 feet high. The natural fault scarps may be frequently very subtle features.

Because natural faults are commonly planes of weakness susceptible to further displacement from subsidence, larger surficial offsets and high fault scarps may occur. Elevation differences on each side of the Hockley escarpment measure as much as 45 feet in 1 mile. Detrimental effects of active faults underneath transportation routes and buildings on land and under or along pipelines in the bay can be significant.

Erosion and Accretion

Erosion is a predominant, nearly ubiquitous, process around Galveston area bays and on Gulf beaches (Table 4) (17,18), except where deltation or spits naturally develop. This erosion and consequent land loss represents the summation of (1) sea-level rise, (2) a wave-dominated shallow bay, (3) episodic tropical storms and northers, and (4) minor subsidence. Land losses along the Gulf shoreline reflect a deficit in sediment supply and relative sea-level rise or compactional subsidence (18). Highest rates of natural accretion occur at the bayhead delta of the Trinity River, where the shoreline advanced as much as 42.6 feet per year between 1851 and 1982.

The largest rates of accretion or erosion are invariably related to human activities. Inordinately

Table 1.4. Erosion and Accretion Rates from Historical Monitoring of Shorelines of the Galveston Bay System.

	Bay Locations					
	1850-52 to 1930		1930 to 1982		1850-52 to 1982	
	No. of stations	Rate (ft/yr)	No. of stations	Rate (ft/yr)	No. of stations	Rate (ft/yr)
Trinity Bay	66	-1.8	60	0.9	60	-0.7
E. Trinity Bay	26	-3.0	25	-1.8	25	-2.6
Lake Anahuac (does not include Trinity delta)	9	-2.9	6	+0.6	6	-0.9
Trinity Delta	10	+3.9	9	+7.2	9	+5.8
W. Trinity Bay	21	-2.6	20	-2.3	20	-2.3
Galveston Bay	57	-2.2	55	-4.2	55	-3.0
West Bay	106	-1.6	98	-2.4	84	-2.0
N. West Bay	23	-2.5	7	-3.8	7	-3.6
Chocolate Bay	15	-1.0	15	-2.4	15	-1.6
W. West Bay	4	-6.5	7	-6.3	4	-7.0
W. peripherals	30	-1.3	29	-1.5	27	-1.6
S. West Bay	34	-0.8	40	-2.1	31	-1.5
East Bay	54	-1.8	48	-3.2	47	-2.1
S. East Bay	30	-2.1	24	-3.7	23	-2.3
N. East Bay	24	-1.4	24	-2.8	24	-1.9

	Gulf Locations					
	1883 to 1930		1930 to 1955		1883 to 1974	
	No. of stations	Rate (ft/yr)	No. of stations	Rate (ft/yr)	No. of stations	Rate (ft/yr)
Bolivar Peninsula	16	-0.3	19	+4.1	16	0.1
	1850 to 1930		1930 to 1956		1838 to 1970	
	No. of stations	Rate (ft/yr)	No. of stations	Rate (ft/yr)	No. of stations	Rate (ft/yr)
Galveston Island	28	-3.3	28	+4.5	28	-2.4

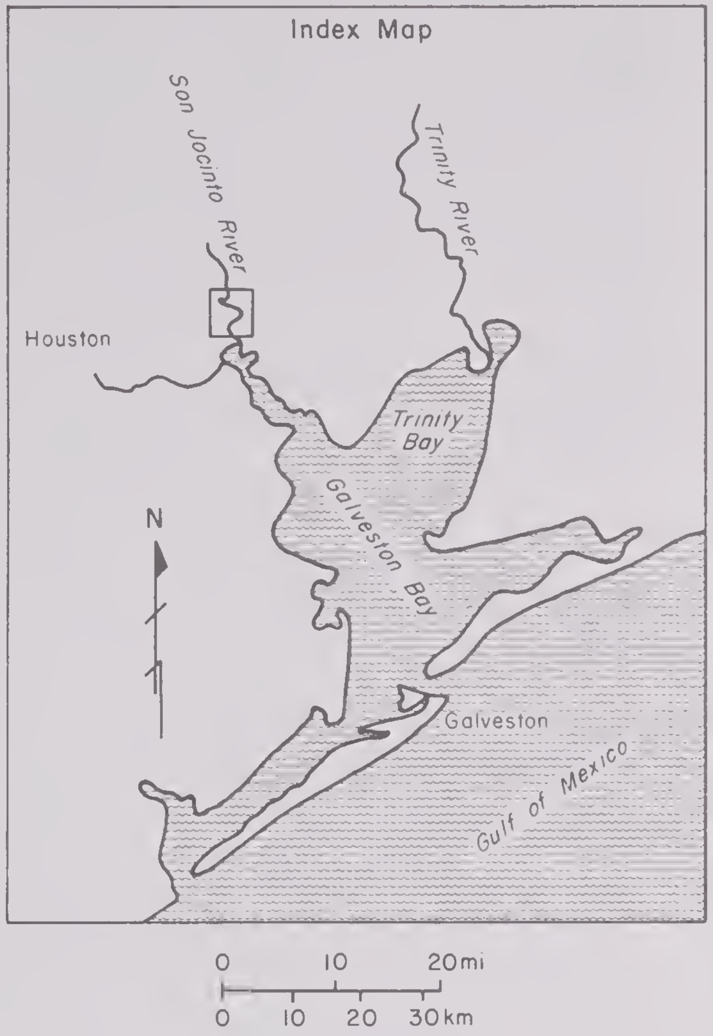
Source: Paine and Morton, 1986 (17) and Morton, 1974 and 1975 (18).

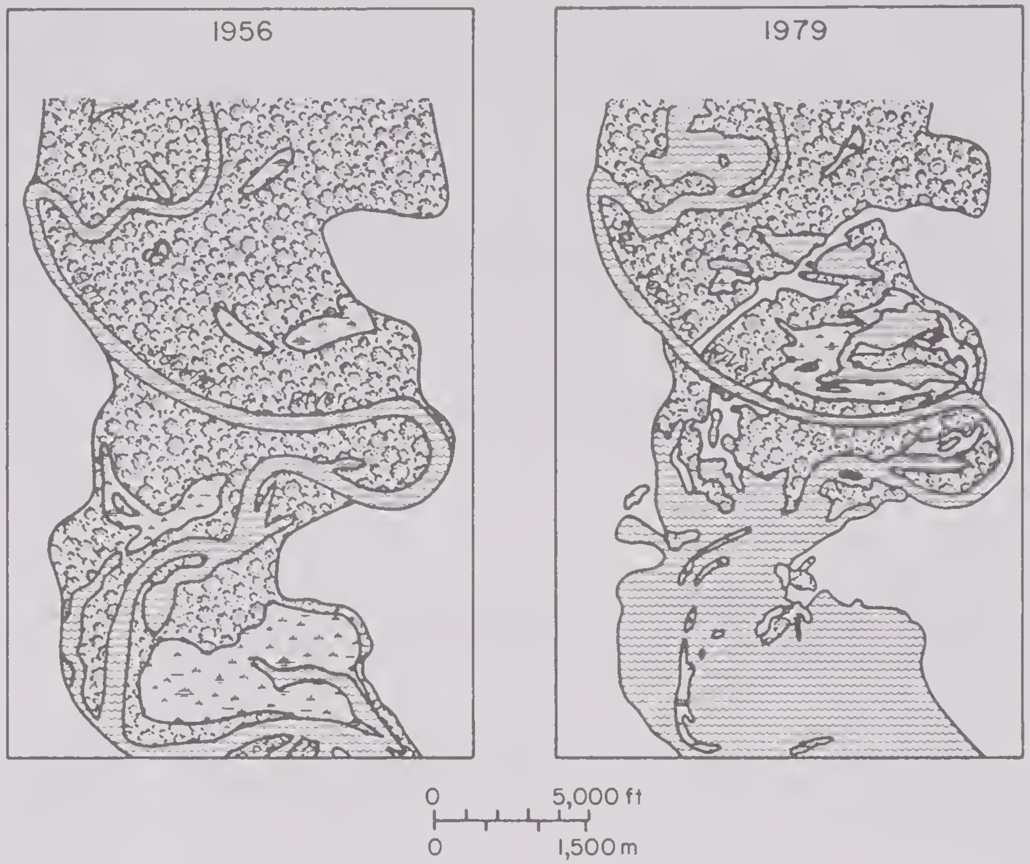
high rates of shoreline accretion adjacent to Bolivar Roads, as much as 28 feet per year on Bolivar Peninsula and 48 feet per year on eastern Galveston Island, were not included in Table 4; coastal engineering structures (e.g., jetties) artificially enhance accretion rates. Similarly, maximum losses of land measured in the bays occur in areas of maximum man-induced subsidence.

Rates of erosion and accretion for the Galveston Bay System were calculated from historical monitoring of shorelines for long time periods. Although effects of hurricanes are averaged into these calculations, the magnitude of work accomplished by a hurricane is not apparent. Since 1900, four hurricanes have centered on Galveston, in 1900, 1947, 1959 and 1983 (11). The unnamed 1900 storm was the most severe (10)—having an approach speed of 10 mph, maximum winds of 125 mph, barometric pressure of 27.64 inches, and a storm surge height of 20 feet. No maps or aerial photographs are available to document erosion and accretion for that storm. However, Carla in 1961 had nearly the same intensity in all categories. A gulfward facing shoreline eroded as much as 800 feet and about 500 feet of sand accreted to the rear shore of the barrier island (20). No bay shoreline measurements were found.

HOUSTON AREA

Changes in the Distribution of Wetlands between 1956 and 1979 for a Segment of the San Jacinto River that has undergone Subsidence





Wetland Map Unit	1956		1979		Net Change	
	Acres	Hectares	Acres	Hectares	Acres	Hectares
Water	875	355	2,295	930	+1,420	+ 575
Fluvial Woodlands & Swamps	3,480	1,410	2,090	845	-1,390	- 565
Fresh to Brackish Marsh	650	265	300	120	- 320	-130

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Figure 1.10. Losses of fluvial wetlands and marshes in the San Jacinto Estuary, between 1954 and 1979, after White and others, 1985 (7).

Erosion and accretion of the Galveston Bay System when Hurricane Alicia struck in 1983 are well documented (12). Compared with Carla, a class IV storm, Alicia was a class III storm (12). In this storm, the eye passed over San Luis Pass. The beach level of West Beach landward of the prestorm vegetation line was lowered about 3 feet by erosion, and the average vegetation-line retreat was nearly 80 feet. Loss of sand for this part of the prestorm beach terrain was 883,750 yards^3. The largest possible erosion in the shortest time from a potential hurricane needs to be part of future Galveston Bay management. Beyond the significance of geologic processes, the effects of Hurricane Alicia on beachfront properties are especially important to landowners and coastal managers.

Recommendations

Although we know much about the physical setting of the Galveston Bay System, conditions that impact people should be widely and repeatedly monitored. For example, the geology and geochemistry of Galveston Bay was sampled only once, in 1976. Resampling and reanalyses are needed to examine human impacts on the chemistry of Galveston Bay further. Continued monitoring of water chemistry, salinities and nutrients is the key to the healthy existence of the bays and their animal populations.

Modern high-resolution seismic profiles of the shallow bay sediments would provide valuable information for permitting future construction. Improved physical measurements of water circulation, especially currents and tides, would enhance bay system management. No long-standing current meters have ever been emplaced at the inlets; salinity and nutrient gradients indicate the need for long-term monitoring of currents in the Houston Ship Channel and at other significant sites. The EPA predictions of expected (drastic?) sea-level rise need immediate attention; ground releveling and tide gauge measurements are required to predict the response of various types of shorelines to increased sea-level changes.

Shoreline changes and sediment influxes that reflect losses of both private property and public wetlands need a new cycle of monitoring in order to develop a holistic management approach. We need additional information on the impacts of major storms for planning emergency responses, and we need to improve predictions of coastal evolution with respect to potential sea-level rise.

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Biological Components of Galveston Bay

Peter F. Sheridan, R. Douglas Slack, Sammy M. Ray, Larry W. McKinney, Edward F. Klima, Thomas R. Calnan[1]

Distribution and Abundance

Estuarine Vegetation

PETER F. SHERIDAN—The plant life of Galveston Bay includes phytoplankton in the water column, benthic microflora, macroalgae, submerged aquatic vegetation and emergent vascular plants. Some groups are so dense that they are major sources of physical structure for other estuarine organisms, while some groups are major producers of organic materials for assimilation by consumers. Other functions of vegetation include refuge from predators, maintenance of water quality by filtering runoff and tidal inputs, and shoreline stabilization.

Phytoplankton—The phytoplankton of upper Galveston and Trinity Bays is composed of at least 132 species, including diatoms (54 taxa), green algae (45 taxa), blue-green algae (14 taxa), dinoflagellates (9 taxa), euglenoids (7 taxa), cryptophytes (2 taxa), and golden-brown algae (1 taxon) (1). Many of these species, particularly the green algae, are freshwater forms entering via river discharge. Over an annual cycle (September 1975-August 1976), the mean percentage of the standing crop for each division was found to be diatoms (41.6 percent), green algae (24.2 percent), blue-green algae (23.0 percent), dinoflagellates (5.9 percent), euglenoids (2.6 percent), and others (2.7 percent). Major peaks in phytoplankton density occurred in late winter and mid-summer. The winter peak was due to the diatoms **Skeletonema costatum** and **Cyclotella menenghiniana**, while the summer peak in densities was due to a bloom of the blue-green **Oscillatoria** sp. As a group, diatoms were the dominant phytoplankters in November, December and February-June (**Skeletonema** and **Cyclotella** in cold months, **Nitzschia closterium**, **Navicula abunda** and **Thalassionema nitzschoides** in warmer months). Green algae were a consistent 20 to 30 percent of the monthly standing crops, and **Ankistrodesmus** sp. bloomed in September-October. Blue-green algae were relatively abundant July to October, and a bloom of **Oscillatoria** in July represented 70 percent of the standing crop. The dinoflagellate **Prorocentrum** sp. comprised 45 percent of the total density in January. Euglenoids such as **Euglena** spp. and **Eutreptia** spp. were relatively abundant in May and August. Lower salinity stations were dominated by blue-green and green algae while high salinity sites were dominated by diatoms.

Similar studies on phytoplankton distribution and abundance have not been conducted in lower Galveston, East or West Bays.

Benthic Microflora—Components of the benthic microflora have been examined in a descriptive sense (2-4), but little information on temporal or spatial distribution is available. Thirty-three genera

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Table 2.1. Benthic Algae Collected from Bay Sediments (2) and Beach Sands (4) in the Galveston Bay System.

Green Algae	Blue-green Algae	Diatoms
Bracteacoccus	Anabaena	Achnanthes (2)
Characium	Anacystis	Actinoptychus (3)
Chlamydomonas	Aphanocapsa	Amphora (3)
Chlorosarcina	Aphanothece	*Coscinodiscus (10)
Chlorosarcinopsis	Calothrix	*Cyclotella (3)
Chlorococcum	Gloeocapsa	Diatoma (1)
Cylindrocystis	Lyngbya	*Diploneis (4)
Eremosphaera	Myxosarcina	Epithemia (1)
Gloeocystis	Nostoc	Eunotogramma (1)
Hormidium	Oscillatoria	Mastogloia (1)
Oedocladium	Schizothrix	Melosira (2)
Pleurastrum	Spirulina	Navicula (4)
Radiosphaera	Synechococcus	Nitzschia (9)
Stichococcus	Synechocystis	Opephora (1)
Tetracystis	Xenococcus	Pinnularia (1)
Tetraedon		Pleurosigma (4)
		Rhopalodia (2)
		*Skeletonema (1)
		Stenopterobia (1)
Cryptophytes	Euglenophytes	Stephanodiscus (1)
Cryptomonas	Euglena	Surirella (1)
		Synedra (1)

(n) = number of species in genus, if given
* = most abundant

of algae were identified from Galveston Island beach sands, and 22 genera (56 species) of diatoms were identified from bay sediments (Table 2.1). The diatoms **Coscinodiscus, Diploneis, Cyclotella** and **Skeletonema** were noted as being very abundant (2), the latter two genera also dominating the phytoplankton as noted previously. Diatoms were the main component of the benthic microflora in waters deeper than 0.5 m, while blue-green algae dominated the shallow water and tidal flats (3). Algal densities could not be related to depth, sediment type, Eh, pH or salinity.

Macroalgae—There has been no survey of macroalgal types over the whole bay system. Several faunal surveys (9, 13, 24) noted that, where present, the macroalgae is represented by **Enteromorpha, Ectocarpus, Dictyota, Sargassum, Polysiphonia** and **Gracilaria**. The major study of macroalgae was limited to Galveston Island proper (46), finding 19 genera and 28 species over a two-year period (Table 2.2). The gulf shore community is composed of **Cladophora, Bryocladia** and **Ceramium** in summer and shifts to **Enteromorpha, Bangia** and **Gelidium** in winter. The bay shore community is barren in the summer and is primarily **Enteromorpha** and **Ectocarpus** during winter. The flora is considered depauperate relative to other Gulf estuaries.

Submerged aquatic vegetation—Submerged aquatic vegetation is limited in areal extent. On the Trinity River delta, the submerged freshwater plants **Vallisneria americana** (tapegrass) and **Sagit-**

Table 2.2. Benthic Macroalgae of Galveston Island Grouped by Maximum Growth Periods(46).

Summer-Fall	Winter-Spring	Indeterminant (not enough data)
Bryocladia cuspidata	Ectocarpus siliculosus	Dictyota dichotoma
Ceramium strictum	Petalonia fascia	Gracilaria foliifera
Cladophora dalmatica	Enteromorpha clathrata	Sargassum fluitans
Cladophora linum	Enteromorpha flexuosa	Sargassum natans
Polysiphonia gorgoniae	Enteromorpha lingulata	Vaucheria sp.
Polysiphonia denudata	Enteromorpha prolifera	
Polysiphonia tepida	Ulva lactuca	
Spyridia filamentosa	Gelidium crinale	
Chaetomorpha linum	Bangia fuscopurpurea	
Erythrocladia subintegra	Polysiphonia subtilissima	
Erythrotrichia carnea		
Goniotrichum alsidii		
Achrochaetium sp.		

taria kurziana (strap-leaf) are currently found in mixed stands (5). **Vallisneria** has also been found in the Chocolate Bay area off West Bay (24). Extensive **Ruppia maritima** (widgeon grass) beds were once located in shallow marginal waters of Trinity Bay and upper Galveston Bay (6-8). East Bay was found to be devoid of submerged vegetation (9). **Ruppia** was also scattered in various embayments along lower Galveston Bay and West Bay (10-13). Western West Bay, Christmas Bay and Bastrop Bay harbored seagrass beds dominated by **Halodule wrightii** (shoal grass) and lesser amounts of **Thalassia testudinum** (turtle grass) and **Halophila engelmannii** (13, 14). The areal extent of submerged vegetation has apparently declined from approximately 21 km^2 around 1960 (6-8, 12) to <1 km^2 by 1979 (15). There have been no studies of seasonal growth or distribution of submerged vegetation in the Galveston Bay system, and no actual bay-wide site surveys for species composition and distribution.

Marshes, woodlands and swamps—Emergent vegetation can be classified as salt, brackish or freshwater marshes, fluvial woodlands and swamps. These wetlands are large-scale contributors to estuarine productivity in terms of particulate matter, nutrients, structure, protection and substrate. Salt marshes cover an estimated 140 km^2 (12). Species such as **Spartina alterniflora, Batis maritima, Salicornia** spp. and **Juncus roemerianus** are most common in the more frequently flooded areas, while **Borrichia frutescens, Monanthochloe littoralis, Distichlis spicata, Suaeda** spp., **Iva** spp. and **Aster** spp. are less common (Table 2.3). **Spartina alterniflora** is the dominant plant in subsiding salt marshes due to almost constant flooding. Brackish marshes (230 km^2; 12) are of moderate salinity regimes (1 to 18 ppt) but are flooded by storm tides from the bay and by freshwater inundation from rainfall and runoff, thus they have a mixture of vegetation types (Table 2.3). Plants frequently occurring in fresher areas include **Scirpus maritimus, S. californicus** and **S. americanus, Alternathera philoxeroides, Bacopa monnieri, Typha** spp., **Paspalum lividum** and **Phragmites australis,** while plants in the more saline brackish marshes include **Spartina patens** and **S. spartinae, Scirpus olneyi** and **S. maritimus, Paspalum vaginatum, Juncus roemerianus** and species from higher salt marshes. Lower elevation brackish marshes are dominated by **Scirpus, Typha, Eleocharis** and **Bacopa,** whereas in higher elevation brackish marshes **Spartina spartinae** and **S. patens** are more common. Fresh marshes are generally beyond all salt water intrusion except during hurricane surges. There are approximately 40 km^2 of fresh marshes, primarily in the Trinity and San Jacinto River systems (12). Low fresh marshes are characterized by **Typha** spp., **Scirpus americanus** and **S.**

Table 2.3. Typical Plants Found in Galveston Bay Wetland Environments (15).

Scientific name	Common name
Salt Marsh	
Spartina alterniflora	smooth cordgrass
Batis maritima	saltwort
Salicornia virginica	glasswort
Salicornia bigelovii	glasswort
Distichlis spicata	seashore saltgrass
Borrichia frutescens	sea-oxeye
Monanthochloe littoralis	shoregrass
Juncus roemerianus	needle rush
Suaeda sp.	seablite or seepweed
Lycium carolinianum	Carolina wolfberry
Spartina spartinae	gulf cordgrass
Spartina patens	marshhay cordgrass
Iva frutescens	bigleaf sumpweed
Iva angustifolia	narrowleaf sumpweed
Limonium nashii	sea-lavender
Scirpus maritimus	salt-marsh bulrush
Sporobolus spp.	dropseed
Sesuvium portulacastrum	sea purslane
Heliotropium curassavicum	salt heliotrope
Brackish Marsh	
Spartina spartinae	gulf cordgrass
Spartina patens	marshhay cordgrass
Borrichia frutescens	sea-oxeye
Distichlis spicata	seashore saltgrass
Monanthochloe littoralis	shoregrass
Scirpus maritimus	salt-marsh bulrush
Scirpus americanus	three-square bulrush
Scirpus californicus	California bulrush
Scirpus olneyi	Olney bulrush
Alternanthera philoxeroides	alligatorweed
Typha domingensis	narrowleaf cattail
Typha latifolia	common cattail
Spartina cynosuroides	big cordgrass
Phragmites australis	common reed
Eleocharis parvula	dwarf spikerush
Cyperus spp.	flatsedge
Enchinochloa crusgalli	barnyard grass
Leptochloa spp.	sprangletop
Bacopa monnieri	coastal waterhyssop
Aster tenuifolius	saline aster
Aster subulatus	saltmarsh aster
Aster spinosus	spiny aster
Paspalum lividum	longtom
Paspalum vaginatum	seashore paspalum
Setaria geniculata	knotroot bristlegrass
Zizaniopsis miliacea	giant cutgrass
Solidago sempervirens	seaside goldenrod
Baccharis halimifolia	groundsel bush
Iva frutescens	bigleaf sumpweed
Iva angustifolia	narrowleaf sumpweed
Iva annua	seacoast sumpweed
Sesuvium portulacastrum	sea purslane
Salicornia spp.	glasswort
Limonium nashii	sea-lavender
Juncus roemerianus	needle rush
Lycium carolinianum	Carolina wolfberry
Sporobolus spp.	dropseed
Fimbristylis castanea	fimbry
Hydrocotyle spp.	pennywort
Fresh Marsh	
Spartina spartinae	gulf cordgrass
Typha latifolia	common cattail
Typha domingensis	narrowleaf cattail
Scirpus americanus	three-square bulrush

Scirpus californicus	California bulrush
Paspalum lividum	longtom
Eleocharis spp.	spikesedge
Cyperus spp.	flatsedge
Alternanthera philoxeroides	alligatorweed
Juncus spp.	rush
Ludwigia spp.	seedbox
Sagittaria spp.	arrowhead
Pontederia sp.	pickerelweed
Polygonum spp.	knotweed
Phragmites australis	common reed
Bacopa monnieri	waterhyssop
Echinodorus spp.	burrhead
Eichhornia crassipes	water hyacinth
Rhynchospora sp.	beakrush
Fimbristylis spp.	fimbry
Echinochloa crusgalli	barnyard grass
Leptochloa spp.	sprangletop
Spartina patens	marshhay cordgrass
Lemna spp.	duckweed
Hydrocotyle spp.	marsh penny-wort
Zizaniopsis miliacea	southern wildrice
Sesbania drummondii	rattlebush
Baccharis halimifolia	groundsel bush
Cephalanthus occidentalis	buttonbush
Salix nigra	black willow

Transitional Areas

Spartina spartinae	gulf cordgrass
Cynodon dactylon	bermudagrass
Borrichia frutescens	sea-oxeye
Aster spinosus	spiny aster
Paspalum monostachyum	gulfdune paspalum
Paspalum lividum	longtom
Panicum spp.	panicum
Rhynchospora spp.	beakrush
Andropogon virginicus	broomsedge bluestem
Andropogon glomeratus	bushy bluestem
Iva annua	seacoast sumpweed
Aristida spp.	threeawn
Setaria spp.	bristlegrass
Helianthus spp.	sunflower
Sorghum halepense	johnsongrass
Cassia fasciculata	partridge pea
Cyperus spp.	flatsedge
Eleocharis spp.	spikesedge
Scirpus spp.	bulrush
Croton spp.	doveweed
Spartina patens	marshhay cordgrass
Baccharis halimifolia	groundsel bush
Sesbania drummondii	rattlebush

Fluvial Woodlands

Salix nigra	black willow
Celtis spp.	hackberry/ sugarberry
Fraxinus spp.	ash
Ulmus crassifolia	cedar elm
Ulmus americana	American elm
Quercus aquatica	water oak
Quercus lyrata	overcup oak
Quercus phellos	willow oak
Quercus stellata	post oak
Quercus virginiana	live oak
Liquidambar styraciflua	sweetgum
Ilex vomitoria	yaupon
Cephalanthus occidentalis	buttonbush
Sapium sebiferum	Chinese tallow
Pinus taeda	loblolly pine
Carya aquatica	water hickory
Carya illinoensis	pecan
Populus deltoides	cottonwood
Plantanus occidentalis	American sycamore
Planera aquatica	water elm
Acacia farnesiana	huisache
Parkinsonia aculeata	retama
Tamarix gallica	salt cedar
Sabal minor	dwarf palmetto
Taxodium distichum	bald cypress
Acer negundo	boxelder

Swamp

Taxodium distichum	bald cypress
Planera aquatica	water elm
Carya aquatica	water hickory
Cephalanthus occidentalis	buttonbush

californicus, Phragmites australis, Eleocharis spp., **Cyperus** spp., **Juncus** spp., **Ludwigia** sp., **Sagittaria** spp. and **Paspalum lividum** (Table 2.3) (1, 15). Higher fresh marshes are typified by **Spartina spartinae, Paspalum** spp., **Polygonum** spp., **Panicum** spp., **Borrichia, Rhynchospora macrostachya, Fimbristylis** sp., **Aster** spp. and **Sesbania drummondii.** Many species of **Spartina** exhibit broad salinity tolerances and are found in several categories of marsh. Fluvial woodlands along floodplains cover 450 km^2 (12) and support a variety of water-tolerant trees and shrubs (Table 2.3), including **Fraxinus** spp., **Salix nigra, Ulmus** spp., **Celtis** spp., **Carya** spp. and **Quercus** spp. Swamps containing saturated soils or nearly permanent standing water comprise 50 km^2 (12) and are dominated by **Taxodium distichum** (Table 2.3). Additional information on wetland plants is also available (16).

Between wetland surveys of 1956 and 1979, several changes were noted in vegetation patterns in the estuary: (1) expansion of open water into former marshes and woodlands; (2) expansion of marshes along the bay side of barrier islands into prior tidal flats; (3) formation of wetlands farther up creek valleys; (4) landward expansion of existing marshes; (5) reduction of submerged vegetation; and (6) reduction or modification of wetlands by human activities (15). Of primary concern are the losses of 63 km^2 of fresh marsh and 42 km^2 of salt and brackish marshes during this period. These losses are ascribed to such activities as channelization, impoundments, filling and subsidence associated with subsurface petroleum or water extraction.

Invertebrates

Invertebrates within the Galveston Bay system are discussed by component groups such as zooplankton, benthos, and mobile and sessile macrofauna. While there have been a number of studies of invertebrates in this area, there are no synoptic zooplankton or macrofaunal surveys on a bay-wide basis.

Zooplankton—A 12-month study of zooplankton in the upper Galveston and Trinity Bay areas (1) revealed 70 species representing nine phyla. The most abundant plankters included copepods (primarily **Acartia tonsa**, followed by **Labidocera, Cyclops** and **Oithoina**) and barnacle nauplii (**Balanus** spp.); in fact, these two phyla plus a mixed assemblage of copepod nauplii and copepodites represented >70 percent of the zooplankton in 11 of 12 months. Other phyla included rotifers (**Asplancha, Brachionus, Keratella**), dinoflagellates (**Noctiluca scintillans**) and larvaceans (**Oikopleura**). Zooplankton densities peaked in April (dominated by copepod nauplii and **Noctiluca**) and August (**Acartia** and copepod nauplii). Barnacle nauplii were most dense in late winter-early spring. Fluctuations in zooplankton densities were not linked to variations in river flow, but salinity regimes regulated species composition and seasonal distribution.

A three-and-a-half-year study (17) of the larger zooplankters in the same region (mouth of the San Jacinto River and southern Trinity Bay) identified 94 taxa dominated by crustaceans and fishes. Crab larvae, tentatively identified as **Rhithropanopeus harrisii**, were the most abundant group followed by other crustaceans such as **Petrolisthes armatus, Pinnixa** sp., **Palaemonetes** spp. and **Callinectes** spp., and by the fishes **Brevoortia patronus** and **Anchoa mitchilli.** Two broad seasonal groups were detected relating to abundance of organisms, with a "warm" season characterized by many larval crustaceans and few fishes and a "cool" season where the reverse trend was found.

A 16-month study of the zooplankton of Christmas Bay (18) indicated that this high salinity embayment hosted a permanent zooplankton assemblage of three species (**Mnemiopsis mccradyi**, a ctenophore, and **Acartia tonsa** and **Oithoina colcarva**, copepods) apparently unaffected by temperature and salinity fluctuations. Other taxa such as larval crustaceans, other copepods, and the ctenophore **Beroë ovata** exhibited summer peaks in abundance.

No zooplankton studies have been conducted in West Bay or East Bay.

Benthos—Six benthic macroinvertebrate assemblages occur in the Galveston Bay complex, including open bay center, oyster reef, grassflat, bay margin, inlet-influenced and river-influenced assemblages (Table 2.4). The river-influenced assemblage covers the greatest area, including all of Trinity Bay, upper Galveston Bay, and part of East Bay. Oyster reef assemblages occur primarily in central Galveston Bay and divide Galveston Bay into upper and lower sections. Lower Galveston Bay contains primarily inlet-influenced and open bay center assemblages. The bay margin assemblage occurs on the bay side of Bolivar Peninsula and near Texas City. All six assemblages are found in West Bay.

The river-influenced assemblage contains a small group of common bay species, including the bivalve **Mulinia lateralis**, the polychaetes **Capitella capitata, Streblospio benedicti** and **Mediomastus** spp., and brackish-water mollusks such as **Macoma mitchelli, Texadina sphinctostoma** and **Rangia flexuosa**. These species occur in parts of estuaries where salinities vary from fresh to brackish over long periods of time. Average salinities in Trinity Bay range from less than 5 ppt to about 10 ppt (15). However, over relatively short periods of time, the river-influenced assemblage is subjected to greater natural salinity fluctuations (0-33 ppt) than are other bay assemblages.

In contrast to the river-influenced assemblage, the inlet-influenced assemblage contains the highest number of species, partly because of more stable salinities. This assemblage, composed primarily of mollusks, contains some species that are restricted to the area of Galveston and East Bays near Bolivar Roads and Rollover Pass and to West Bay near San Luis Pass. Common species include mollusks such as **Mulinia lateralis, Lyonsia hyalina, Mysella planulata, Turbonilla** sp., **Acteocina canaliculata** and **Nassarius acutus** and polychaetes such as **Owenia fusiformis, Paraprionospio pinnata, Clymenella torquata** and **Mediomastus californiensis**.

The oyster reef assemblage is found primarily on or near reefs and is dominated by the American oyster **Crassostrea virginica** and the mollusks **Ischadium recurvum, Brachidontes exustus** and **Mulinia lateralis**. The common polychaetes **Mediomastus californiensis** and **Streblospio benedicti** are also abundant.

The bay margin assemblage is limited to shallow, sandy stations in East and West Bays and lower Galveston Bay. Most stations are less than 2 km from shore and less than 1 meter deep. Crustaceans such as **Ampelisca** spp., **Cerapus tubularis** and **Oxyurostylis salinoi** are more abundant in the bay margin assemblage than in any other assemblage except the grassflat assemblage.

Crustaceans are dominant in the grassflat assemblage and include such species as **Ampelisca abdita, Acanthohaustorius** sp. and **Cymadusa compta**. Bivalves such as **Amygdalum papyrium, Lyonsia hyalina** and **Laevicardium mortoni** and polychaetes such as **Aricidea fragilis** and **Scoloplos fragilis** are common. Grassflats are of limited distribution in the Galveston Bay system and occur principally in patches along the margin of the Trinity River delta and Christmas Bay.

The open bay center assemblage occurs in lower Galveston Bay and East and West Bays in muddy sediments and in relatively deep water. Polychaetes are the predominant group and are characterized by **Paraprionospio pinnata, Parandalia fauveli** and **Podarkeopsis levifuscina**.

A 12-month study of the benthos of Trinity Bay (1) indicated that polychaetes were the most speciose group collected (35 species), followed by crustaceans (18 species), mollusks (14 species), and bryozoans, rhynchocoels and chordates (5 species). Seventy-four percent of all individuals collected were polychaetes, primarily **Mediomastus californiensis** and other capitellids. Other abundant species were the mollusks **Macoma** sp., **Amnicola** sp. and **Texadina sphinctostoma**. Densities of benthic organisms exhibited spring and late summer peaks.

Macroinvertebrates—These mobile and sessile species are rarely encountered using the plankton or benthic sampling methods involved in prior sections except as larval or early juvenile forms. No synoptic surveys of macroinvertebrates in the Galveston Bay system (other than oysters, **Crassostrea virginica**) have been conducted. The public oyster reefs within the estuary have been described (19, 20). The reefs are typically long and narrow, are oriented perpendicular to water currents, and are densest in the mid-bay region and across the mouth of East Bay. Settlement of spat (free-swimming larvae) generally occurs during April to November, primarily in the summer months. Oysters reach market size in 13 to 18 months. The distribution of oyster reefs depends on the interactions of temperature, salinity, predation and disease (19). High salinities allow an increased predation by oyster drills (**Thais haemastoma**) and increased infection by **Perkinsus marinus** ("dermo"). Extensive periods of low salinity can also kill oysters, so most of the viable reefs are located in areas characterized by 10 to 20 ppt mean annual salinity. Since 1975, the areal distribution of oyster reefs has been stable.

Although not well documented, there are numerous species of mobile macroinvertebrates in the estuary (13, 21-24) (Table 2.5). All of these species were collected in western West Bay (but are found elsewhere) and many of these species are probably limited to submerged vegetation or oyster reef habitats, rarely caught elsewhere. In shallow, fringing habitats **Palaemonetes** spp. (grass shrimp) are most common and reach maximum abundance in March through July. **Macrobrachium ohione**

Table. 2.4. Characteristic Species in Macroinvertebrate Assemblages (15).

Galveston-Trinity-East Bays

River-Influenced

Bivalves
- Mulinia lateralis
- Macoma mitchelli
- Rangia flexuosa

Gastropods
- Texadina sphinctostoma
- Vioscalba louisianae
- Texadina barretti

Polychaetes
- Parandalia fauveli
- Streblospio benedicti
- Capitella capitata
- Mediomastus californiensis
- Polydora ligni

Crustaceans
- Corophium louisianum

Inlet-Influenced

Bivalves
- Mulinia lateralis
- Lyonsia hyalina floridana
- Tellina texana

Gastropods
- Turbonilla cf. T. interrupta
- Nassarius acutus

Polychaetes
- Owenia fusiformis
- Apoprionospio pygmaea
- Onuphis eremita oculata

Bay Margin

Bivalves
- Amygdalum papyrium

Polychaetes
- Streblospio benedicti
- Paraprionospio pinnata
- Tharyx marioni
- Owenia fusiformis

Crustaceans
- Oxyurostylis salinoi
- Monoculodes nyei
- Cerapus tubularis
- Hargeria rapax

Open Bay Center

Bivalves
- Mulinia lateralis

Polychaetes
- Paraprionospio pinnata
- Pseudeurythoe ambigua
- Parandalia fauveli
- Sigambra spp.

Crustaceans
- Acetes americanus

Oyster Reef

Gastropods
- Boonea impressa
- Texadina sphinctostoma

Bivalves
- Crassostrea virginica
- Ischadium recurvum
- Brachidontes exustus
- Mulinia lateralis

Polychaetes
- Nereis succinea
- Polydora ligni
- Mediomastus californiensis
- Streblospio benedicti
- Parandalia fauveli

Crustaceans
- Melita nitida
- Rhithropanopeus harrisii
- Cassidinidea lunifrons

West Bay (including Chocolate, Christmas and Bastrop Bays)

Grassflat

Bivalves
- Amygdalum papyrium
- Laevicardium mortoni

Polychaetes
- Chone duneri
- Nereis succinea
- Streblospio benedicti

Crustaceans
- Ampelisca abdita
- Edotea montosa
- Cerapus tubularis
- Listriella sp.

Oyster Reef

Bivalves
- Crassostrea virginica
- Ischadium recurvum

Polychaetes
- Nereis succinea

Crustaceans
- Grandidierella bonnieroides
- Oxyurostylis salinoi
- Rhithropanopeus harrisii

River-Influenced

Gastropods
- Texadina barretti

Bivalves
- Macoma mitchelli
- Mulinia lateralis

Polychaetes
- Parandalia fauveli
- Scoloplos fragilis
- Paraprionospio pinnata
- Glycinde solitaria

Open Bay Center

Bivalves
- Mulinia lateralis
- Mysella planulata
- Lyonsia hyalina floridana

Polychaetes
- Paraprionospio pinnata
- Podarkeopsis levifuscina
- Cossura delta
- Mediomastus californiensis
- Melinna maculata

Inlet-Influenced

Gastropods
- Turbonilla cf. T. interrupta
- Acteocina canaliculata

Bivalves
- Mulinia lateralis
- Periploma margaritaceum
- Mysella planulata
- Lyonsia hyalina floridana

Polychaetes
- Paraprionospio pinnata
- Clymenella torquata
- Owenia fusiformis
- Mediomastus californiensis

Crustaceans
- Ampelisca brevisimulata

Bay Margin

Gastropods
- Acteocina canaliculata
- Acteon punctostriatus

Bivalves
- Mulinia lateralis
- Ensis minor
- Lyonsia hyalina floridana

Polychaetes
- Mediomastus californiensis

Crustaceans
- Ampelisca abdita
- Ampelisca brevisimulata
- Oxyurostylis salinoi

Table 2.5. Macrocrustaceans Collected in Trawl Surveys of the Galveston Bay System (13, 21-23).

Stomatopods	Crabs
Squilla empusa	Petrolisthes armatus
	Clibanarius vittatus
Shrimp	Pagurus longicarpus
Penaeus setiferus	Pagurus pollicaris
Penaeus aztecus	Ovalipes stephensoni
Penaeus duorarum	Callinectes sapidus
Trachypenaeus similis	Callinectes similis
Xiphopenaeus kroyeri	Menippe mercenaria
Alpheus heterochaelis	Rhithropanopeus harrisii
Palaemonetes pugio	Hexapanopeus angustifrons
Palaemonetes vulgaris	Neopanope texana
Palaemonetes intermedius	Eurypanopeus depressus
Macrobrachium ohione	Panopeus herbstii
Periclimenes longicaudatus	Pachygrapsus transversus
Hippolyte zostericola	Uca spp.
Tozeuma carolinense	Libinia dubia
	Heterocrypta granulata

Table 2.6. Comparison of the Most Numerous Fishes Collected During a Two-Year Period in Various Galveston Bay Habitats (Rank Order) (27).

Channels	Open Bay
Stellifer lanceolatus	Micropogonias undulatus
Micropogonias undulatus	Anchoa mitchilli
Symphurus plagiusa	Cynoscion arenarius
Anchoa mitchilli	Stellifer lanceolatus
Polydactylus octonemus	Arius felis
Arius felis	Sphoeroides parvus
Menticirrhus americanus	Citharichthys spilopterus
Brevoortia patronus	Leiostomus xanthurus
Citharichthys spilopterus	Symphurus plagiusa
Leiostomus xanthurus	Polydactylus octonemus
Nearshore Flats	Peripheral Lagoons and Bayous
Micropogonias undulatus	Micropogonias undulatus
Anchoa mitchilli	Anchoa mitchilli
Leiostomus xanthurus	Leiostomus xanthurus
Arius felis	Cynoscion arenarius
Sphoeroides parvus	Mugil cephalus
Brevoortia patronus	Citharichthys spilopterus
Cynoscion arenarius	Brevoortia patronus
Citharichthys spilopterus	Arius felis
Menticirrhus americanus	Symphurus plagiusa
Stellifer lanceolatus	Sphoeroides parvus

(river shrimp) is found in low salinity areas during April and May. Postlarval **Penaeus aztecus** (brown shrimp) enter the estuary in February through April, move into shallow nurseries, and then reappear in large numbers in open bay waters during March through July. **Penaeus setiferus** (white shrimp) postlarvae begin entering the estuary in April and juveniles become most numerous in open waters during July through November. A small population of **Penaeus duorarum** (pink shrimp) enters as larvae to shallow estuarine nurseries in the fall and juveniles are recaptured in March through May in open bay waters. **Callinectes sapidus** (blue crab) is most susceptible to sampling gear in October through April but may recruit almost all year. One species not included in Table 2.5 but quite important to the system is **Lolliguncula brevis** (brief squid). It is a summer inhabitant of higher salinity waters (9) and may be an important determinant of community composition as a predator (25).

Vertebrates

This section encompasses fishes, birds, amphibians, reptiles and mammals, but only fishes have been the object of synoptic surveys.

Fishes—A comprehensive list of the ichthyofauna of the Galveston Bay system encompassed 66 families, 122 genera and 162 species (26). Freshwater fishes (9 families, 19 species) rarely found in the bay were included. Results of a two-year, synoptic trawl survey (27) indicated that, of 96 species recorded, six species accounted for 91 percent of the total number of fishes collected: **Micropogonias undulatus** (Atlantic croaker, 51 percent); **Anchoa mitchilli** (bay anchovy, 22 percent); **Stellifer lanceolatus** (star drum, 8 percent); **Leiostomus xanthurus** (spot, 4 percent); **Cynoscion arenarius** (sand seatrout, 3 percent); and **Arius felis** (hardhead catfish, 3 percent). These six species plus **Mugil cephalus** (striped mullet) were responsible for 74 percent of the biomass collected, dominated by **Micropogonias** (37 percent of the weight) over all others (<10 percent each). In general, the same small group of 13 species dominated catches in various bay habitats (Table 2.6). The total fish fauna was most numerous in April and May (dominated by **Micropogonias**) and least dense in December and January (dominated by **Anchoa**). Biomass peaks generally occurred May through August (**Micropogonias, Stellifer**), while the biomass of a mixed assemblage was lowest in November. Although no surveys have addressed West Bay proper, surveys of Chocolate Bayou (24) and Christmas Bay (13) revealed 72 and 83 species of fishes, respectively, with similar dominant species.

Larval and postlarval fishes often numerically dominate zooplankton collections. The same species that later comprise the bulk of the trawl catches are usually the most abundant as plankters (17, 18, 28).

Birds—Although no comprehensive study of the avifauna of the Galveston Bay system has been conducted, observers and checklists have recorded 139 bird species associated with wetlands and bay habitats (29, 30). This group of species accounts for 25 percent of the 565 bird species recorded for Texas (31). Further, these wetland-related forms do not include the large number of terrestrial resident or migratory birds. Three large groups of birds have a significant representation in the Galveston Bay system—waterfowl, shorebirds and colonial nesting waterbirds.

Waterfowl are censused each January during the Mid-winter Waterfowl Survey, a cooperative effort between the Texas Parks and Wildlife Department and the U.S. Fish and Wildlife Service. These surveys have shown that 60 percent of Texas' wintering waterfowl are found on the upper Texas coast, including large populations of **Chen caerulescens** (snow goose), associated with rice-growing regions of the coastal prairies (32). Aerial surveys of the Galveston Bay system for the years 1978 and 1984 through 1987 have recorded an average of 11,500 waterfowl annually. The five most common species observed during these surveys were **Anas crecca** (green-winged teal), **Aythya collaris** (ring-necked duck), **Aythya affinis** (lesser scaup), **Mergus serrator** (red-breasted merganser), and **Oxyura jamaicensis** (ruddy duck). Although a total of 32 species of waterfowl has been observed in the bay system (Table 2.7), only **Dendrocygna bicolor** (fulvous whistling duck), **Anas fulvigula** (mottled duck), **Aix sponsa** (wood duck), and **Anas discors** (blue-winged teal) are regular breeders in the area. The remaining species of waterfowl use the estuary during migration or while overwintering.

The Galveston Bay system has been identified by the Western Hemisphere Shorebird Reserve Network as a regionally significant reserve site (34), denoting support of >5 percent of all mid-continental shorebird populations during migration. Large populations of migrating or overwinter-

Table 2.7. Waterfowl Observed in the Galveston Bay System (32, 33).

Common Name	Scientific Name	Common Name	Scientific Name
Fulvous whistling duck	Dendrocygna bicolor	American wigeon	Anas americana
Black-bellied whistling duck	Dendrocygna autumnalis	Canvasback	Aythya valisineria
Greater white-fronted goose	Anser albifrons	Redhead	Aythya americana
Snow goose	Chen caerulescens	Ring-necked duck	Aythya collaris
Ross' goose	Chen rossii	Greater scaup	Aythya marila
Canada goose	Branta canadensis	Lesser scaup	Aythya affinis
Wood duck	Aix sponsa	Old squaw	Clangula hyemalis
Green-winged teal	Anas crecca	Black scoter	Melanitta nigra
Mottled duck	Anas fulvigula	Surf scoter	Melanitta perspicillata
Mallard	Anas platyrhynchos	White-winged scoter	Melanitta fusca
Northern pintail	Anas acuta	Common goldeneye	Bucephala clangula
Blue-winged teal	Anas discors	Bufflehead	Bucephala albeola
Cinnamon teal	Anas cyanoptera	Hooded merganser	Lophodytes cucullatus
Northern shoveler	Anas clypeata	Red-breasted merganser	Mergus serrator
Gadwall	Anas strepera	Ruddy duck	Oxyura jamaicensis
		Masked duck	Oxyura dominica

Table 2.8. Shorebirds Recorded for the Galveston Bay System (33, 34).

Common Name	Scientific Name	Common Name	Scientific Name
Black-bellied plover	Pluvialis squatarola	Long-billed curlew	Numenius americanus
Lesser golden-plover	Pluvialis dominica	Marbled godwit	Limosa fedoa
Snowy plover	Charadrius alexandrinus	Hudsonian godwit	Limosa haemastica
Wilson's plover	Charadrius wilsonia	Ruddy turnstone	Arenaria interpres
Semipalmated plover	Charadrius semipalmatus	Red knot	Calidris canutus
Piping plover	Charadrius melodus	Sanderling	Calidris alba
Killdeer	Charadrius vociferus	Semipalmatedsandpiper	Calidris pusilla
American oyster-catcher	Haematopus palliatus	Western sandpiper	Calidris mauri
Black-necked stilt	Himantopus mexicanus	Least sandpiper	Calidris minutilla
American avocet	Recurvirostra americana	White-rumped sandpiper	Calidris fuscicollis
Greater yellowlegs	Tringa melanoleuca	Baird's sandpiper	Calidris bairdii
Lesser yellowlegs	Tringa flavipes	Pectoral sandpiper	Calidris melanotos
Solitary sandpiper	Tringa solitaria	Dunlin	Calidris alpina
Willet	Catoptrophorus semipalmatus	Stilt sandpiper	Calidris himantopus
Spotted sandpiper	Actitis macularia	Buff-breasted sandpiper	Tryngitis subruficollis
Upland sandpiper	Bartramia longicauda	Short-billed dowitcher	Limnodromus griseus
Eskimo curlew	Numenius borealis	Long-billed dowitcher	Limnodromus scolopaceus
Whimbrel	Numenius phaeopus	Common snipe	Gallinago gallinago
		American woodcock	Scolopax minor
		Wilson's phalarope	Phalaropus tricolor
		Red-necked phalarope	Phalaropus lobatus
		Red phalarope	Phalaropus fulicaria

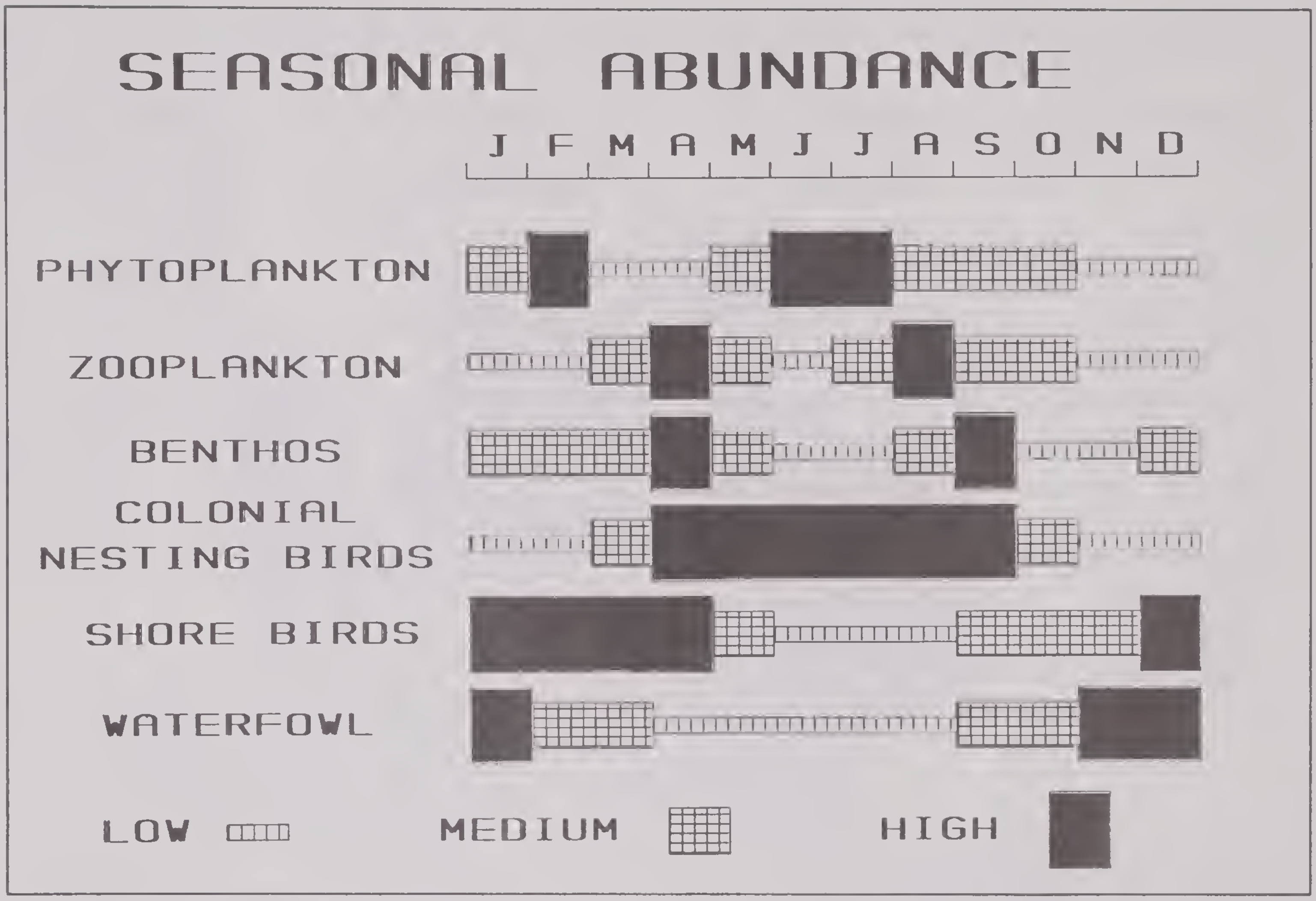

Figure 2.1. Seasonality of the components of the benthic food web in relation to the abundance of Galveston Bay avifauna (1, 17, 33, 34, 35, 36, 64).

ing shorebirds utilize intertidal flats on Bolivar Peninsula and on the east and west ends of Galveston Island. Of the 35 species of shorebirds reported for Galveston Bay (Table 2.8), the most common forms are **Pluvialis squatarola** (black-bellied plover), **Recurvirostra americana** (American avocet), **Catoptrophorus semipalmatus** (willet), **Calidris alba** (sanderling), **Calidris mauri** (western sandpiper), **Calidris alpina** (dunlin), and **Limnodromus** spp. (dowitchers) (64). Peaks in shorebird utilization of Galveston Bay occur during the winter months through spring migration (December through May). Chronology of migration and intertidal flat use may be tied to macrobenthic prey phenology (Figure 2.1). Six species of shorebirds are known to nest in the bay complex: **Charadrius wilsonia** (Wilson's plover), **Charadrius vociferus** (killdeer), **Haematopus palliatus** (American oystercatcher), **Himantopus mexicanus** (black-necked stilt), willet and American avocet.

Surveys of colonial nesting waterbirds in the Galveston Bay system have been conducted since 1967 (33, 35). During the period 1973 through 1987 (Figure 2.2), numbers of pairs of colonial nesting waterbirds varied from lows of approximately 39,000 in 1978 and 1985 to a high of 71,700 in 1982 with a mean of 52,136 (33). Active colony numbers have increased from 20 in 1973 to 42 in 1987. Colony sites include gravel and shell bars, **Spartina alterniflora** marshes, cypress stands, dredged material islands, and industrial and developed locations. Twenty-two species of colonial nesting waterbirds have been reported as nesting during the 21 years of surveys (Table 2.9). The three most common species during the 1986 nesting season were **Larus atricilla** (laughing gull), **Sterna maxima** (royal tern) and **Bubulcus ibis** (cattle egret) (36).

Birds that have been identified as threatened or endangered by the U.S. Fish and Wildlife Service (33) include **Pelecanus occidentalis** (brown pelican), **Charadrius melodus** (piping plover), **Numenius borealis** (eskimo curlew), **Sterna antillarum** (interior least tern), **Haliaeetus leucocephalus** (bald eagle), **Falco peregrinus** (peregrine falcon), and **Mycteria americana** (wood stork).

Amphibians and Reptiles—Ninety-two species of amphibians and reptiles have been reported for the four counties surrounding Galveston Bay (37). Mueller (38) described only 15 species of amphibians and reptiles from nontidal wetlands on Galveston Island, however. The American

Table 2.9. Colonial Nesting Waterbirds of the Galveston Bay System (36).

Common Name	Scientific Name	Common Name	Scientific Name
Olivaceous cormorant	Phalacrocorax olivaceus	White ibis	Eudocimus albus
Anhinga	Anhinga anhinga	White-faced ibis	Plegadis chihi
Great blue heron	Ardea herodias	Roseate spoonbill	Ajaia ajaja
Great egret	Casmerodias albus	Laughing gull	Larus atricilla
Snowy egret	Egretta thula	Gull-billed tern	Sterna nilotica
Little blue heron	Egretta caerulea	Caspian tern	Sterna caspia
Tricolored heron	Egretta tricolor	Royal tern	Sterna maxima
Reddish egret	Egretta rufescens	Sandwich tern	Sterna sandvicensis
Cattle egret	Bubulcus ibis	Forster's tern	Sterna forsteri
Black-crowned night-heron	Nycticorax nycticorax	Least tern	Sterna antillarum
Yellow-crowned night-heron	Nycticorax violaceus	Black skimmer	Rynchops niger

Table 2.10. Game and Furbearing Mammals of the Four Counties Surrounding Galveston Bay (41, 42).

Common Name	Scientific Name	Common Name	Scientific Name
White-tailed deer	Odocoileus virginianus	Red fox	Vulpes vulpes
Virginia opossum	Didelphis virginiana	Gray fox	Urocyon cinereoargenteus
Beaver	Castor canadensis	Long-tailed weasel	Mustela frenata
Muskrat	Ondatra zibethicus	Mink	Mustela vison
Nutria	Myocaster coypus	Eastern spotted skunk	Spilogale putorius
Raccoon	Procyon lotor	Striped skunk	Mephitis mephitis
Ringtail	Bassariscus astutus	River otter	Lutra canadensis
Coyote	Canis latrans	Bobcat	Felis rufus

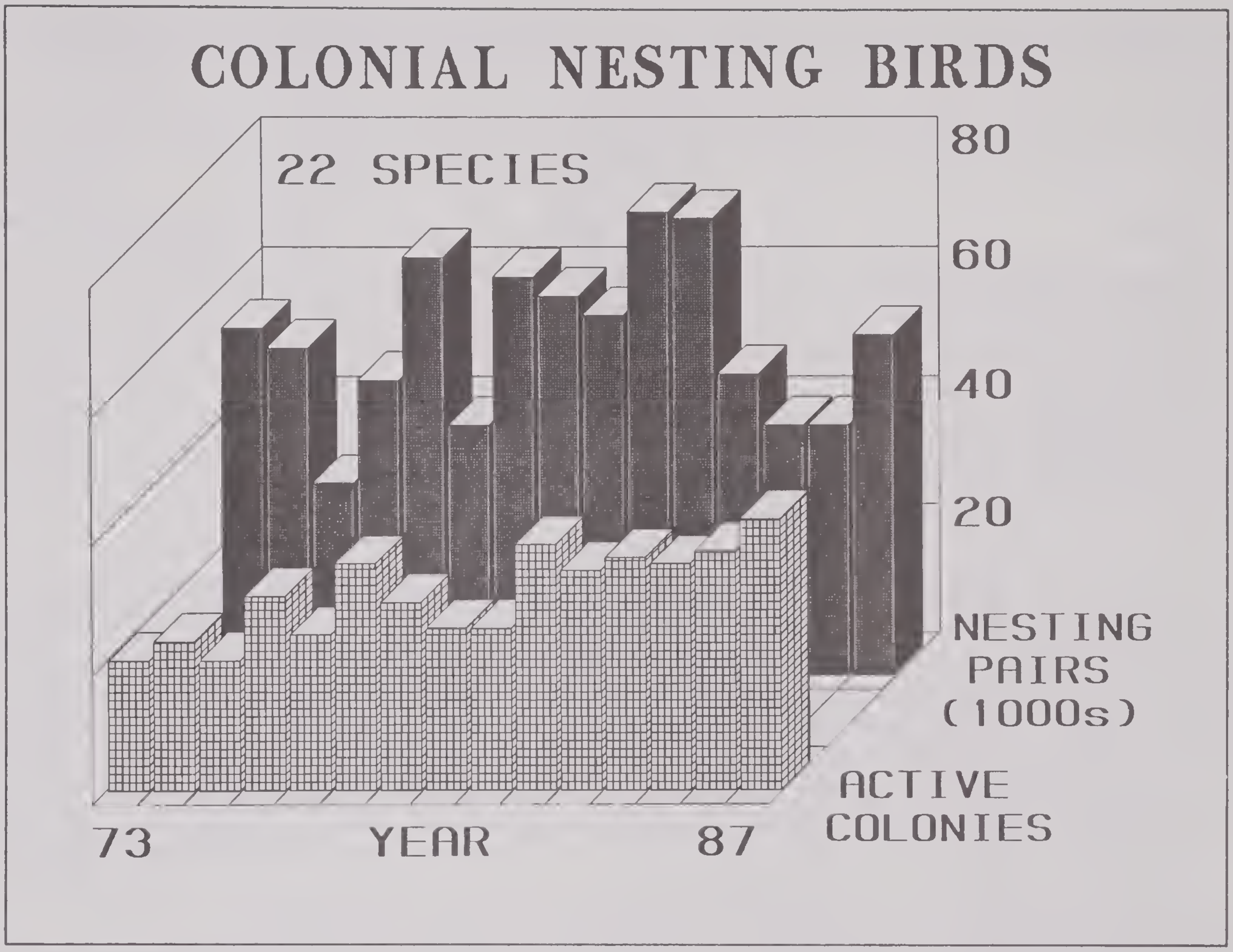

Figure 2.2. Abundance of colonial nesting birds during 1973-1987 (33, 35).

alligator (**Alligator mississippiensis**) has recently become a harvestable animal under state statutes (39). During 1984-1986, a total of 655 alligators were harvested from the counties surrounding the estuary, with 384 (59 percent) taken in freshwater marshes of Chambers County.

Reptiles that frequent the system and have been identified as threatened or endangered by the U.S. Fish and Wildlife Service (33) include: **Dermochelys coriacea** (leatherback sea turtle), **Lepidochelys kempi** (Kemp's ridley sea turtle), **Caretta caretta** (loggerhead sea turtle) and **Chelonia mydas** (green sea turtle). Sea turtles were once an important component of the bay system, so much so that there was a commercial sea turtle fishery in Galveston Bay during the 1890's (40).

Mammals—Schmidly (41, 42) documents 54 species of mammals for the counties surrounding Galveston Bay. Of these, 15 are furbearers and one is a game species (Table 2.10). The mammals most dependent upon wetlands environments include **Sylvilagus aquaticus** (swamp rabbit), **Sciurus carolinensis** (gray squirrel), **Castor canadensis** (beaver), **Ondatra zibethicus** (muskrat), **Rattus rattus** (roof rat), **Oryzomys palustris** (northern rice rat), **Myocastor coypus** (nutria), **Procyon lotor** (raccoon), **Mustela vison** (mink), **Lutra canadensis** (river otter), and **Tursiops truncatus** (bottlenosed dolphin).

Dynamics and Interactions

Some of the relationships of organisms to their physical environments were considered previously, but the interactions of groups of organisms with extrinsic factors such as temperature, salinity, substrate and habitat availability need to be emphasized. This section will generally follow the trophic structure of the estuary.

Primary Productivity

The relative contribution of each floral component to total system primary production has been

Table 2.11. Primary Productivity in the Galveston Bay System (Data Sources in Parentheses).

Flora	Average Estimated Primary Productivity (g dry/m²/yr)	Areal Coverage (km²)	Estimated Annual Production (metric tons)
Phytoplankton (44,45,47)	350	1,425	498,750
Benthic microflora (44,47)	500	1,425	712,500
Submerged vegetation (1,15,48)	2,600	1	2,600
Freshwater marsh (1,12)	820	40	32,800
Salt-Brackish Marsh (12,43)	1,100	370	407,000
Woodlands/swamps (12,47)	700	500	350,000

roughly estimated in Table 2.11. Phytoplankton, benthic microflora, salt and brackish marshes, and woodlands and swamps each contribute roughly the same order of magnitude of organic materials to annual production. Fresh marshes produce an order of magnitude less, while seagrasses contribute two orders of magnitude less production than the four main components. Some of the assumptions made in constructing Table 2.11 need testing, such as productivity of phytoplankton and benthic microflora within Galveston Bay and presumption that such productivity occurs under the total bay surface of 1,425 km^2 (550 mi^2). Within the various habitats, the variation in productivity can be dramatic. For example, in the fresh marsh **Sagittaria graminea** produces 215 g dry/m^2/year while **Phragmites australis** produces 2,984 g dry/m^2/year (1), and in the salt marsh **Batis maritima** produces 425 g dry/m^2/year while **Spartina** spp. produce 1,100 g dry/m^2/year (43). The most productive component, the seagrasses, are the least abundant in this estuary.

Most of the plant production is separated in space and time from the consumer community. In fact, some of that production may never reach the consumers due to inundated regimes and tissue storage. It has been estimated that woodlands, swamps and freshwater marshes export only 8 to 10 percent of the annual aboveground production whereas the frequently inundation low salt marshes may export 30 to 45 percent annually (1, 47). The low nutritional quality, refractory nature of much of the biomass, and resistance to direct grazing all increase from phytoplankton and algae through submerged aquatic vegetation to emergent vascular plants of the salt marsh and woodlands. Thus, the primary consumption of most of the plant biomass is only available along the detritus pathway. Although many organisms play major roles in breaking down this refractory material, they rarely directly assimilate the organic plant matter and, instead, utilize the surface microbial decomposers (47).

Primary Consumption

Less than 10 percent of emergent vegetation of these wetlands is consumed directly, and most of the grazers are insects (47). **Ondatra zibethicus** (muskrat) and **Myocastor coypus** (nutria) are other direct consumers. Submerged vegetation may be directly consumed by a small number of aquatic organisms (snails, fishes such as **Lagodon rhomboides** [pinfish]) as well as certain species of ducks. Phytoplankton are directly grazed by many zooplankters and planktivorous fishes, while benthic algae and epiphytes are utilized by snails, fiddler crabs and other organisms (47). The vast majority of primary consumers in the system are detritivores, species that directly or indirectly consume detrital particles and, lacking the necessary digestive enzymes, in reality utilize only the surface bacteria and fungi. This group includes many benthic organisms (bivalves, gastropods, crustaceans) and bottom feeding fishes and macroinvertebrates (47).

The available evidence suggests that the phytoplankton-based branch of the food web may not be as important to the Galveston Bay system as is the emergent marsh-detritus branch, even though annual primary production may be similar for both groups. First, average phytoplankton densities

are on the low end of the scale for Texas estuaries (1), which are, in turn, on the low end of the range of estuarine production in general (44). Second, zooplankton densities (the main consumers of phytoplankton) are also on the low end of the ranges seen in other Texas estuaries (1). Third, salt marsh productivity is higher in Texas than in most other Atlantic and Gulf coast states (63). Finally, the macrobenthic and fish faunas are omnivores or carnivores except in their earliest larval stages (47).

Habitat Utilization

Vegetated habitats serve other functions than providing direct or indirect sources of food. Aside from these, wetlands function as natural water treatment plants for nutrients and wastes, provide aesthetic value, control biogeochemical cycles of elements such as nitrogen and sulphur, buffer inlands from storms and reduce flooding, and provide useful products such as lumber. Perhaps the most significant functions of wetlands for estuarine organisms are provision of nursery areas for feeding, refuge and substrate utilization by other organisms. In a **Spartina alterniflora** marsh, densities of crustaceans such as **Palaemonetes pugio, Callinectes sapidus** and **Penaeus aztecus** and fishes such as **Lagodon rhomboides, Fundulus** spp., **Sciaenops ocellatus** and **Cynoscion nebulosus** were all significantly higher in flooded marsh areas than in adjacent non-vegetated waters (23, 49). During most seasons, densities of juveniles of many commercially, recreationally and ecologically important fishes and crustaceans are higher in vegetated habitats such as salt marshes, fresh marshes and seagrasses around Galveston Bay than in adjacent open waters (Figure 2.3, from 50). There are indications that the vegetative structure provides refuge from predators and foods (such as epiphytic algae and high densities of infauna) not found in open waters (50-52). The connection between amounts of vegetated habitats and fisheries productivity in adjacent waters has been demonstrated worldwide. For example, landings of brown shrimp in nearshore Louisiana waters have been directly linked to the amount of salt marsh vegetation present (53). Thus, wetlands habitats are quite valuable in many aspects.

Fisheries

The Galveston Bay system supports a wide variety of species in its bay and nearshore commercial and recreational fisheries (Table 2.12). In 1986, commercial fisheries landed more than 10,000 metric tons of seafood with a dockside value exceeding $26 million for the top 10 species alone (Table 2.13). The commercial catches were dominated by invertebrates such as brown shrimp, pink shrimp and white shrimp (totaling 6.8 million kilograms), blue crabs (1.4 million kilograms) and oysters (1.6 million kilograms, whole) (54). Southern and gulf flounders and Atlantic croaker were the dominant finfishes. The 1986 recreational fisheries landed in excess of 280 tons, primarily of sportfishes such as spotted seatrout, sand seatrout, southern and gulf flounders, Atlantic croaker and redfish (55).

Since 1960, landings of penaeid shrimp, oysters and blue crabs have been relatively stable given some degree of annual fluctuation (Figure 2.4) (54, 56). Some abrupt changes have been due to regulatory actions such as closing of bays to oyster harvesting after heavy rainfall and pollutant loading. An apparent upward trend in shrimp landings is in part due to increasing inshore fishing effort but may also indicate increasing marsh access (discussed later). Fluctuations in finfish landings since 1975 (Figure 2.5) (54, 55) were primarily due to regulatory actions in the face of heavy commercial and recreational fishing pressure on spotted seatrout (**Cynoscion nebulosus**) and redfish (**Sciaenops ocellatus**) in the late 1970's. Commercial landings of spotted seatrout and redfish were banned, thus the decline seen around 1980. The commercial fishery is now increasing, with flounders the dominant species and mullets, Atlantic croaker, black drum and sheepshead next in importance. Recreational fishing, now controlled by size and bag limits on certain species, has stabilized and is led by landings of spotted seatrout followed by sand seatrout, redfish, flounders and Atlantic croaker.

A synopsis of commercial and recreational fisheries (Figure 2.6) indicates that landings are generally highest in summer and fall months, with the exception of oysters that are a winter-spring harvest with public reefs closed during the warm months. The blue crab fishery reaches a maximum in early summer. The bait shrimp fishery is most productive in summer and fall, coincidently when both demand and supply are highest. The bay commercial shrimp fishery has two seasons separated by closures: a June and July fishery for brown shrimp (**Penaeus aztecus**) and an August through

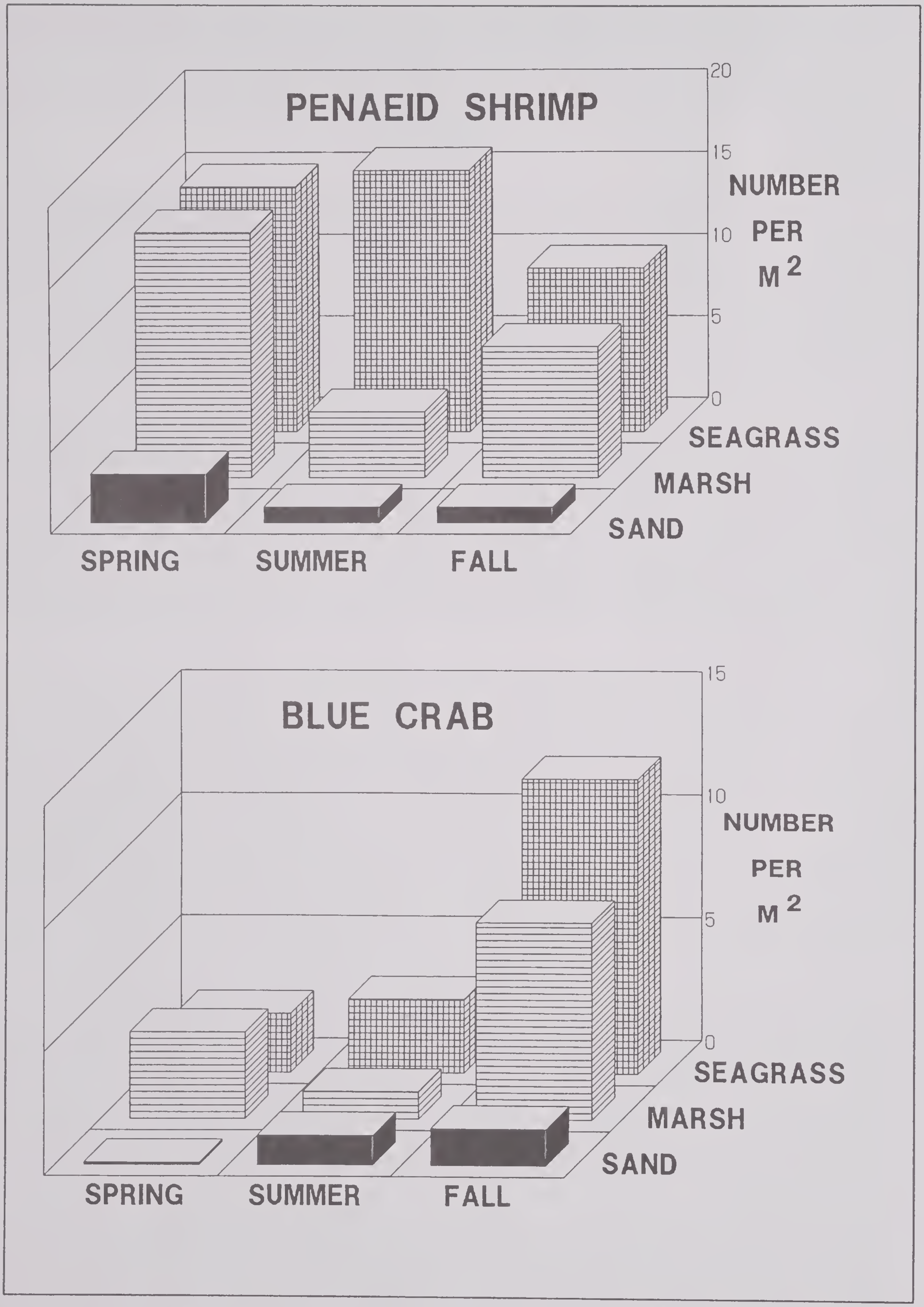

Figure 2.3. Habitat selection by penaeid shrimp (Penaeus spp.) and blue crabs (Callinectes sapidus) in various aquatic habitats of the Galveston Bay estuary (50).

Table 2.12. List of Common and Scientific Names of Commercial and Recreational Finfish and Shellfish Caught or Landed in Texas (54, 55).

Common Name	Scientific Name
Finfish	
African pompano	Alectis alaiis
Alligator gar	Lepisosteus spatula
Atlantic croaker	Micropogonias undulatus
Atlantic cutlassfish	Trichiurus lepturus
Atlantic moonfish	Selene setapinnis
Atlantic needlefish	Strongylura marina
Atlantic spadefish	Chaetodipterus faber
Atlantic stingray	Dasyatis sabina
Black drum	Pogonias cromis
Bluefish	Pomatomus saltatrix
Blue catfish	Ictalurus furcatus
Channel catfish	Ictalurus punctatus
Cobia	Rachycentron canadum
Codfish	Family Gadidae
Dolphin	Coryphaena hippurus
Flounder	
Gulf flounder	Paralichthys albigutta
Southern flounder	Paralichthys lethostigma
Florida pompano	Trachinotus carolinus
Freshwater drum	Aplodinotus gruniens
Gafftopsail catfish	Bagre marinus
Greater amberjack	Seriola dumerilli
Grouper	
Black grouper	Mycteroperca bonaci
Jewfish	Epinephelus itajara
Nassau grouper	Epinephelus striatus
Scamp	Mycteroperca phenax
Warsaw grouper	Epinephelus nigritus
Yellowedge grouper	Epinephelus flavolimbatus
Yellowfin grouper	Mycteroperca venenosa
Yellowmouth grouper	Mycteroperca interstitialis
Gulf butterfish	Peprilus burti
Hardhead catfish	Arius felis
Kingfish	
Gulf kingfish	Menticirrhus littoralis
Southern kingfish	Menticirrhus americanus
Ladyfish	Elops saurus
Largemouth bass	Micropterus salmoides
Little tunny	Euthynnus alletteratus
Mackerel	
King mackerel	Scomberomorus cavalla
Spanish mackerel	Scomberomorus maculatus
Menhaden	Brevoortia patronus
Mullet	
Striped mullet	Mugil cephalus
White mullet	Mugil curema
Ocellated flounder	Ancylopsetta quadrocellata
Permit	Trachinotus falcatus

Table 2.12. (Continued)

Common Name	Scientific Name
Pigfish	Orthopristis chrysoptera
Pinfish	Lagodon rhomboides
Red drum	Sciaenops ocellatus
Seatrout	
Sand seatrout	Cynoscion arenarius
Silver seatrout	Cynoscion nothus
Spotted seatrout	Cynoscion nebulosus
Shark	
Atlantic sharpnose	Rhizoprionodon terraenovae
Blacktip	Carcharhinus limbatus
Bull	Carcharhinus leucas
Great hammerhead	Sphyrna mokarran
Scalloped hammerhead	Sphyrna lewini
Shortfin mako	Isurus oxyrinchus
Smooth dogfish	Mustelis canis
Sheepshead	Archosargus probatocephalus
Silver perch	Bairdiella chrysoura
Smallmouth buffalo	Ictiobus bubalus
Smooth puffer	Lagocephalus laevigatus
Snapper	
Lane snapper	Lutjanus synagris
Red snapper	Lutjanus campechanus
Vermilion snapper	Rhomboplites aurorubens
Southern stingray	Dasyatis americanus
Spot	Leiostomus xanthurus
Striped burrfish	Chilomycterus schoepfi
Swordfish	Xiphias gladius
Tilefish	Lopholatilus chameleonticeps
Triggerfish, gray	Balistes capriscus
Tripletail	Lobotes surinamensis
Tuna	
Blackfin tuna	Thunnus atlanticus
Bluefin tuna	Thunnus thynnus
Yellowfin tuna	Thunnus albacares
Wahoo	Acanthocybium solanderi
Shellfish	
Atlantic bay scallop	Argopecten irradians
Crab	
Blue crab	Callinectes sapidus
Stone crab	Menippe mercenaria
American oyster	Crassostrea virginica
Shrimp	
Brown shrimp	Penaeus aztecus
White shrimp	Penaeus setiferus
Pink shrimp	Penaeus duorarum
Rock shrimp	Sicyonia brevirostris
Royal red shrimp	Hymenopenaeus robustus
Seabob	Xiphopenaeus kroyeri
Squid	
Brief squid	Lolliguncula brevis
Long-finned squid	Loligo pealei

Table 2.13. Landings by Galveston Bay Fisheries During 1986, Including Bay and Nearshore Waters (NMFS Statistical Subarea 18). Landings (Kilograms, kg) and Ex-vessel Value ($) Are in Thousands. ? = Ex-vessel Value Not Available (54, 56).

	Commercial		Recreational	
	Kg	$	Kg	$
Flounder	73	157	39	52
Atlantic croaker	18	9	37	11
Spotted seatrout	-	-	102	?
Sand seatrout	-	-	57	?
Redfish	-	-	43	?
Oysters	1,610	6,950	?	?
Blue crabs	1,375	1,043	?	?
Shrimp (3 species)	6,820	18,135	?	?

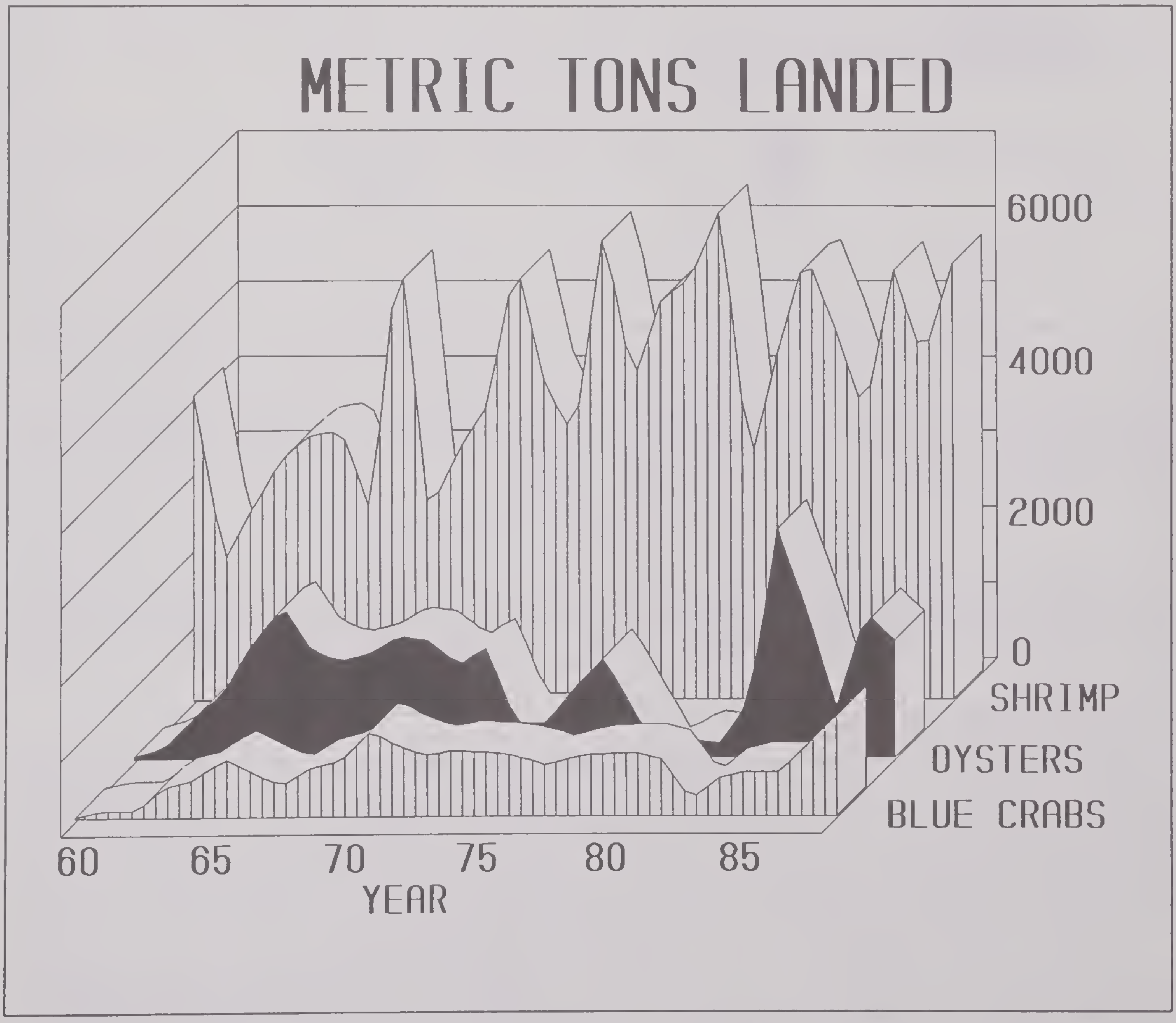

Figure 2.4. Annual landings (1960-1986) of blue crabs, oysters and three species of penaeid shrimp from Galveston Bay and nearshore waters (54, 56).

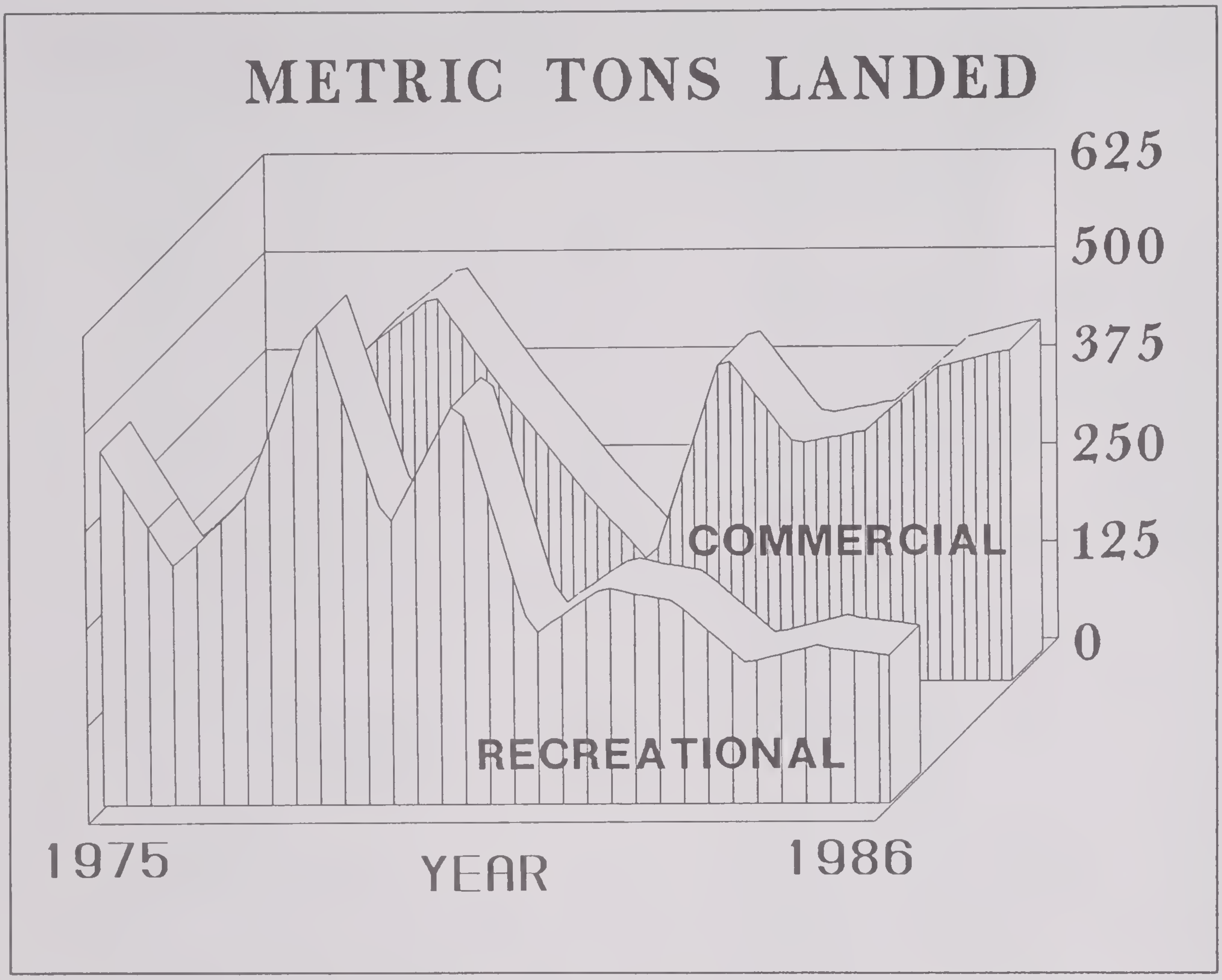

Figure 2.5. Annual landings (1975-1986) of commercial and recreational finfishes from Galveston Bay and nearshore waters (54, 56).

October fishery for white shrimp (P. setiferus). Recreational finfish fisheries are most productive in summer (spotted seatrout, redfish) and fall (flounder). Commercial finfish harvests are highest in the fall, concentrating on flounder, mullet and Atlantic croaker.

Ecological Interactions and Problems

The greatest problems involved in the maintenance of the Galveston Bay biota are related to human utilization of estuarine resources such as wetlands, fresh water and coastal habitats. Each of these areas presents its own unique interactions and prospects for various scenarios of the future status of the bay.

Sea Level Rise and Wetlands Loss

One of the critical problems facing the Galveston Bay estuary is apparent sea level rise (a combination of rapid, local subsidence of land due to groundwater and petroleum withdrawal (15) and slow, oceanic water rise from glacial melting) and associated wetlands loss. As pointed out in previous sections, many estuarine inhabitants depend on wetlands for food, refuge or living space. In 1979, the area containing the estuary's wetlands had elevations of 0 to 1.6 meters above mean sea level and encompassed some 740 square kilometers (Figure 2.7) (15).

The result of the combined forces of subsidence and glacial melting has led to a moderate projection of a 1.0- to 1.6-meter sea level rise by the year 2100 (57). If a 1.6-meter rise were experienced, the new wetlands area (0- to 1.6-meter elevations) would decrease in size by more than 50 percent to 360 square kilometers (Figure 2.8), assuming inland migration of the vegetation. The old 0- to 1.6-meter elevations would be converted to open bay water. However, this new wetlands area is

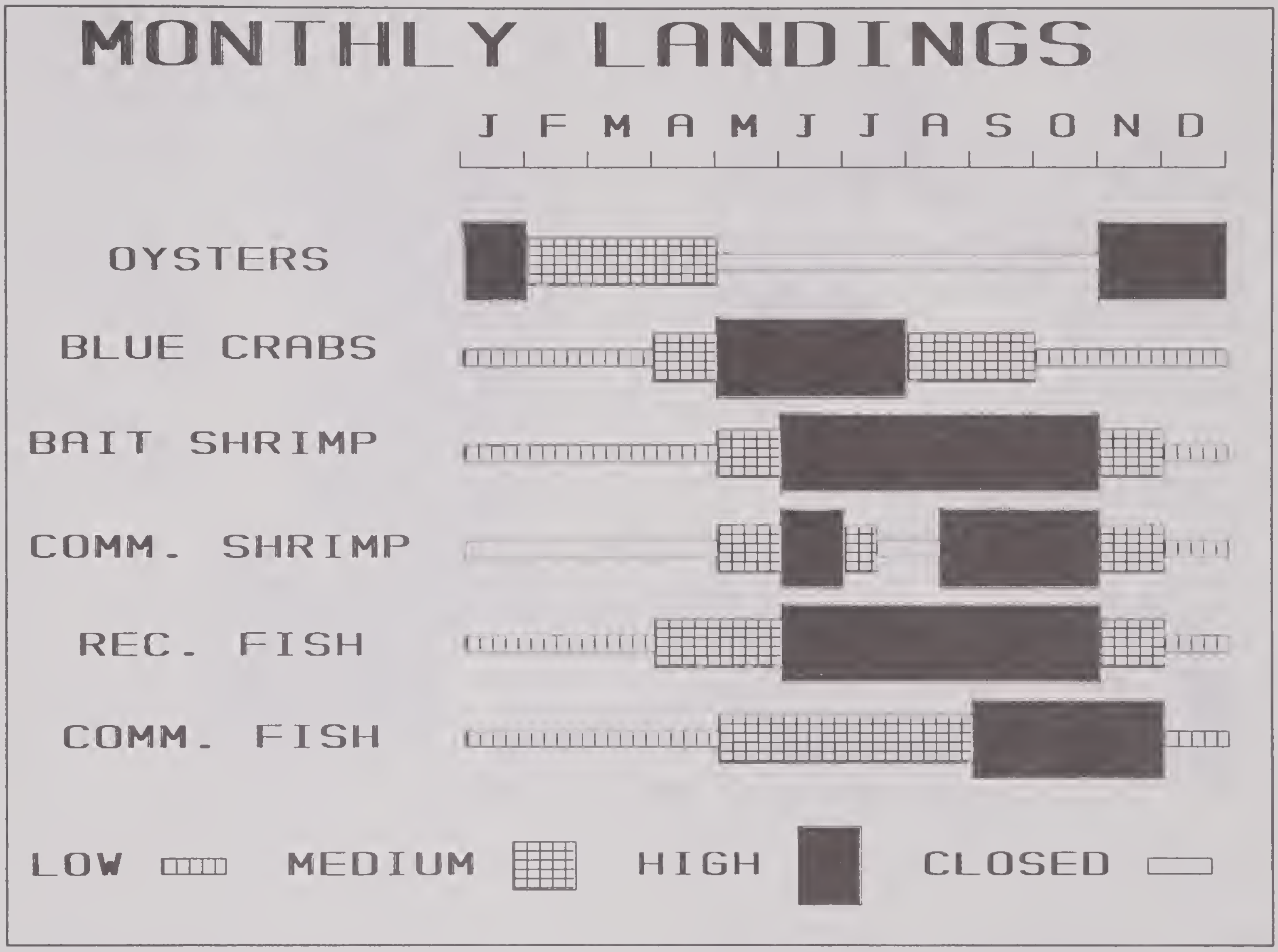

Figure 2.6. Seasonal landings by commercial (comm.) and recreational (rec.) fisheries in Galveston Bay (54, 56).

precisely where houses, industry, bulkheads and other of man's accomplishments are now located. Thus, the actual wetlands area will be much less than 360 square kilometers.

What does this signify for fisheries and for estuary-dependent species in general? As sea level rises and marsh retreat is impeded by civilization, the acreage of wetlands accessible to fishery organisms and contributing to their life cycles will decline, and shortly thereafter so will the fisheries that are currently harvested (58). In the meantime, marshes will be inundated for increasing amounts of time and thus will become "drowning" marshes on the way to extinction. This is a temporarily beneficial situation for the various fishes, invertebrates, birds, reptiles and mammals that utilize the marsh surface, since marsh utilization may be promoted by increases in (1) estuarine area, (2) duration of flooding and thus access, and (3) marsh-open water interface for materials exchanges. In other words, for an interim period greater marsh access could lead to greater system productivity (58).

Galveston Bay itself may be too small to detect the results of apparent sea level rise, although as mentioned previously shrimp catches are increasing and may be due in part to increased marsh access. However, on a Gulf of Mexico basis, the increased access to marshes due to drowning has led to detectable increases in recruitment of at least three commercial species for which a long-time series of data is available — gulf menhaden, brown shrimp and white shrimp (Figure 2.9) (58). From 1960 through 1985, catch statistics and population analyses have detected a 200 percent increase in the number of young gulf menhaden harvested and 50 percent increases in abundances of newly recruited shrimps. The effects of marsh disintegration are beginning to show up.

Freshwater Inflow and Saltwater Intrusion

Another problem facing the Galveston Bay biota is that of controlling fresh water and the associated change in salt water distribution. Two species of economic importance that are especially influenced by fresh water are oysters and white shrimp.

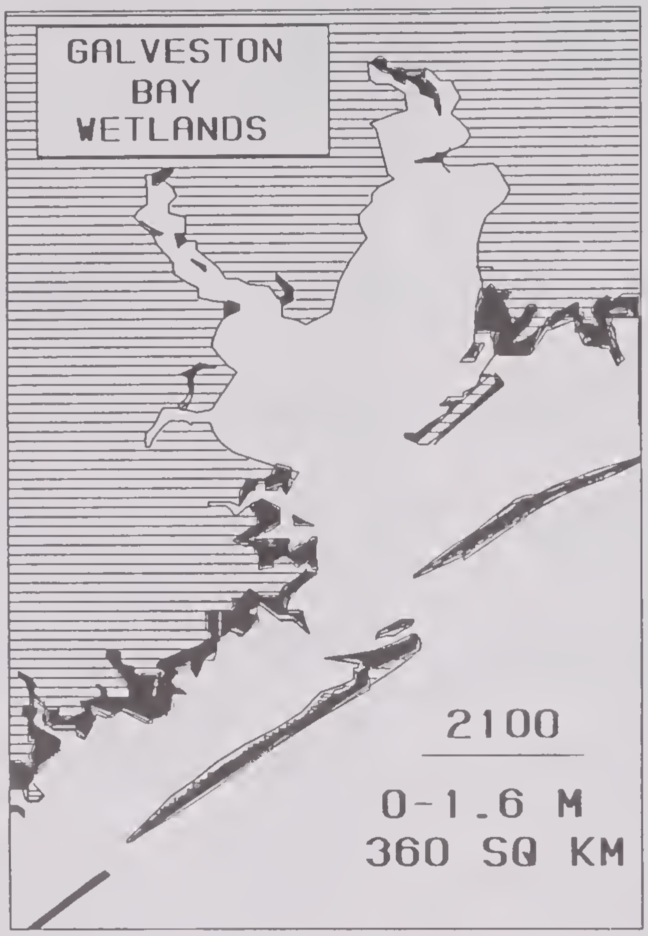

Figure 2.7. Low elevation areas (0-1.6 meters, shaded) where Galveston Bay wetlands were located in 1979, barring development (15).

Figure 2.8. Low elevation areas (0-1/6 meters, shaded) where future Galveston Bay wetlands could exist, barring development, after a 1.6-meter rise in sea level by the year 2100 (15).

Oyster survival and production are excellent indicators of the natural patterns of mixing of fresh and salt waters (19, 20). Under ideal situations oysters survive and grow well at salinities of 10 to 35 ppt. However, salinities of more than 20 ppt bring predators (such as oyster drills) and disease (such as "dermo") that decrease survival and production. Fresh water kills are also incurred if salinities drop below 10 ppt for extended periods or at the wrong time of year. The net result is the typical pattern of oyster reef formation primarily where waters are consistently 10 to 20 ppt. Major shifts in the seasonal timing or amounts of discharge from river systems could cause long-term changes in oyster reef distribution and production.

To a constricted arm of the Galveston Bay system, such as West Bay, a freshet of unrestricted flow can be quite beneficial for oysters. West Bay had been a high salinity-low production bay until a July 1979 tropical storm dropped 110 cm of rain in 24 hours (59). Salinities were dramatically lowered and, combined with subsequent high settlement of oyster spat, reported oyster harvest jumped from zero to1,225 metric tons in the November 1982 through April 1983 season and 907 metric tons the following season (Figure 2.10) (60). Since then, salinities have increased and reported oyster harvest has tapered off.

When fresh water inflow patterns are artificially altered, the results may not be so beneficial to white shrimp productivity. Sabine Lake is located between Galveston Bay and Lake Calcasieu, Louisiana. Dams were built on the Sabine and Neches Rivers in 1965-1966 that contained the natural peak river flows of January through May for later release in generating electricity in the normally low flow period of June through October (61). Portions of the surrounding marshes were also leveed off at the same time. These summer flood conditions negated recruitment of white shrimp to nursery areas by artificially lowering salinities to unacceptable levels. The Sabine Lake white shrimp fishery collapsed, while fisheries in Galveston Bay and Lake Calcasieu continue (Figure 2.11) (56).

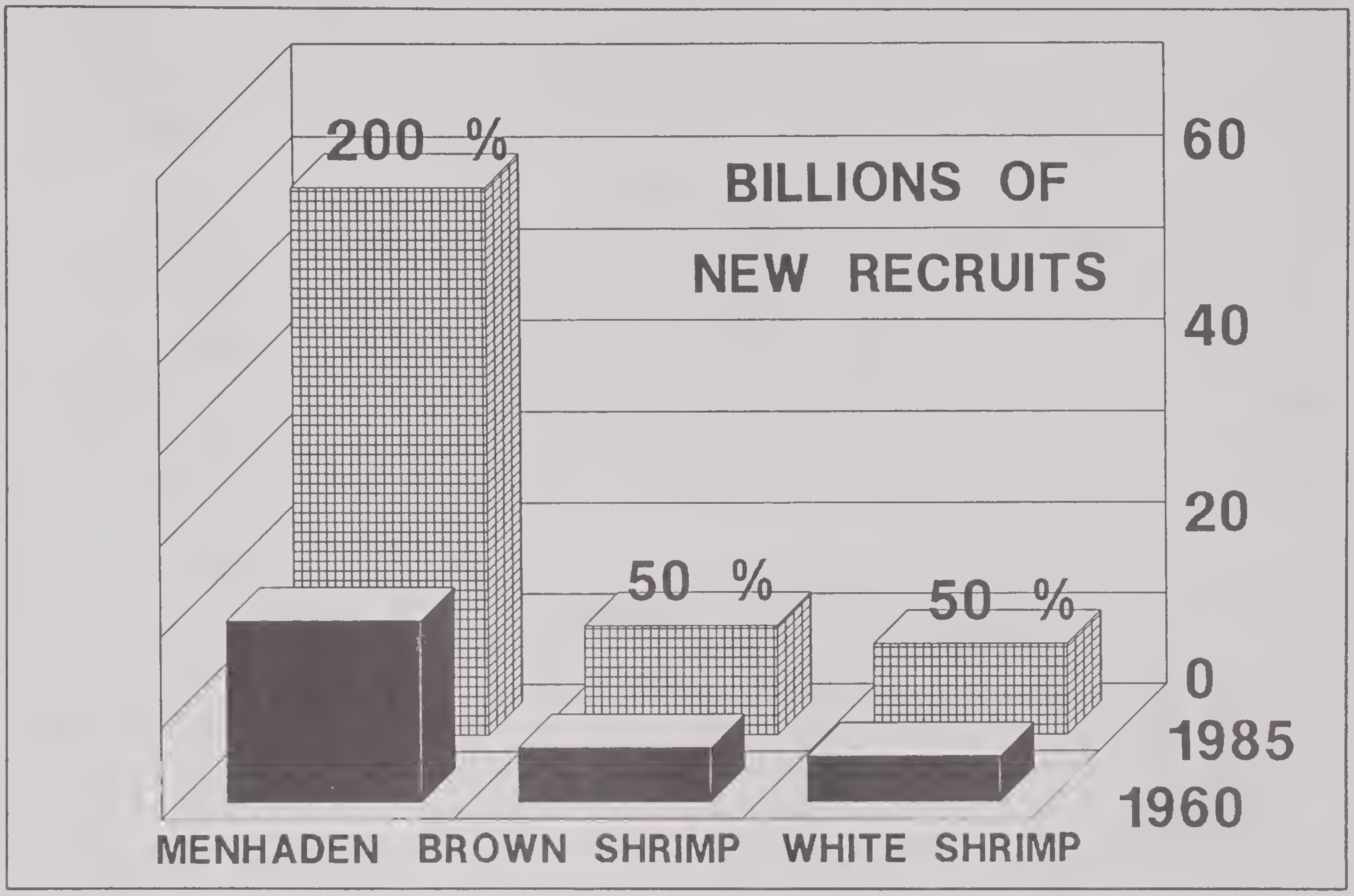

Figure 2.9. Increases in recruitment of menhaden, brown shrimp and white shrimp to U.S. Gulf of Mexico fisheries between 1960 and 1985 (58).

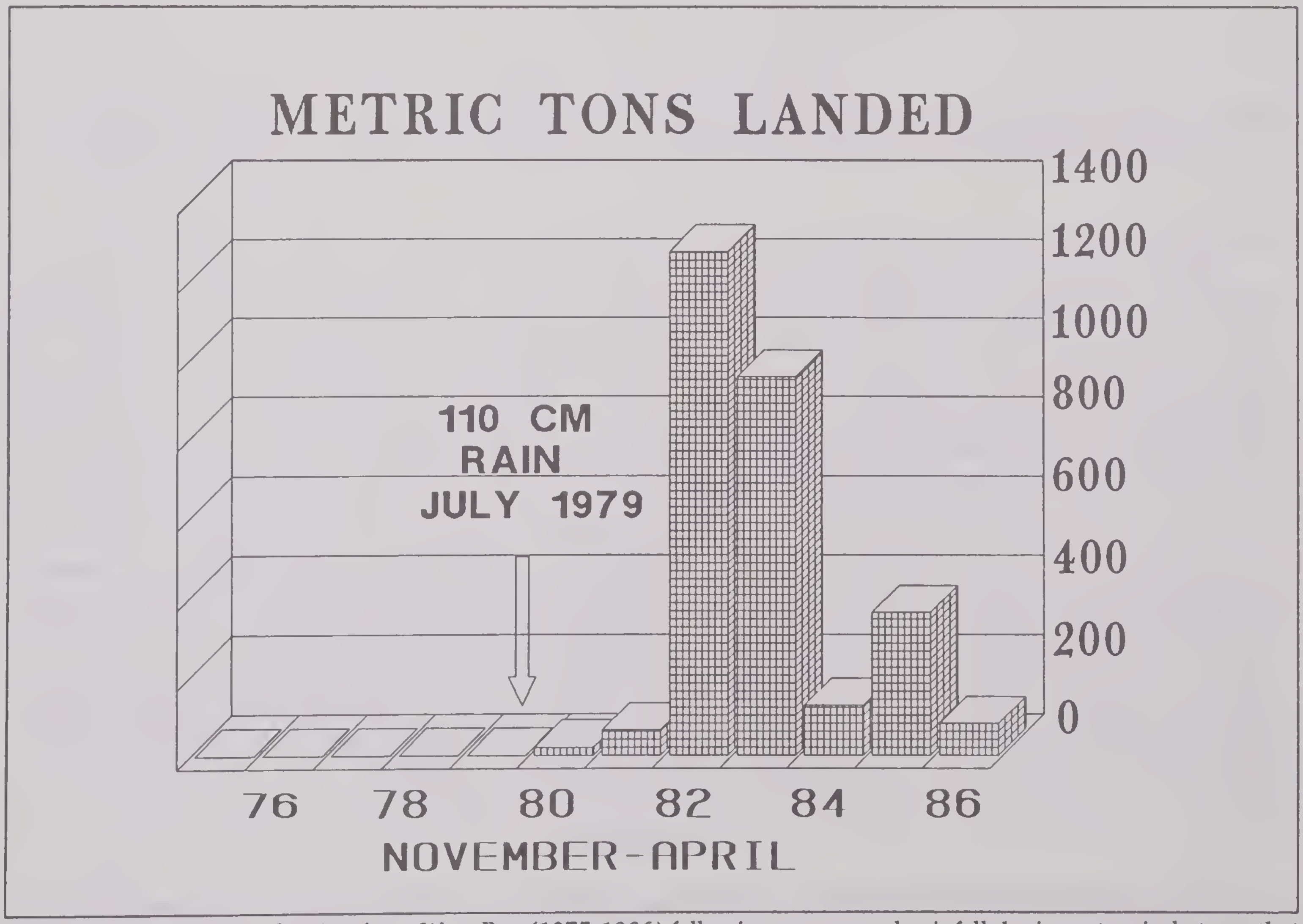

Figure 2.10. Oyster production from West Bay (1975-1986) following an unusual rainfall during a tropical storm that lowered bay salinities for an extended period (60).

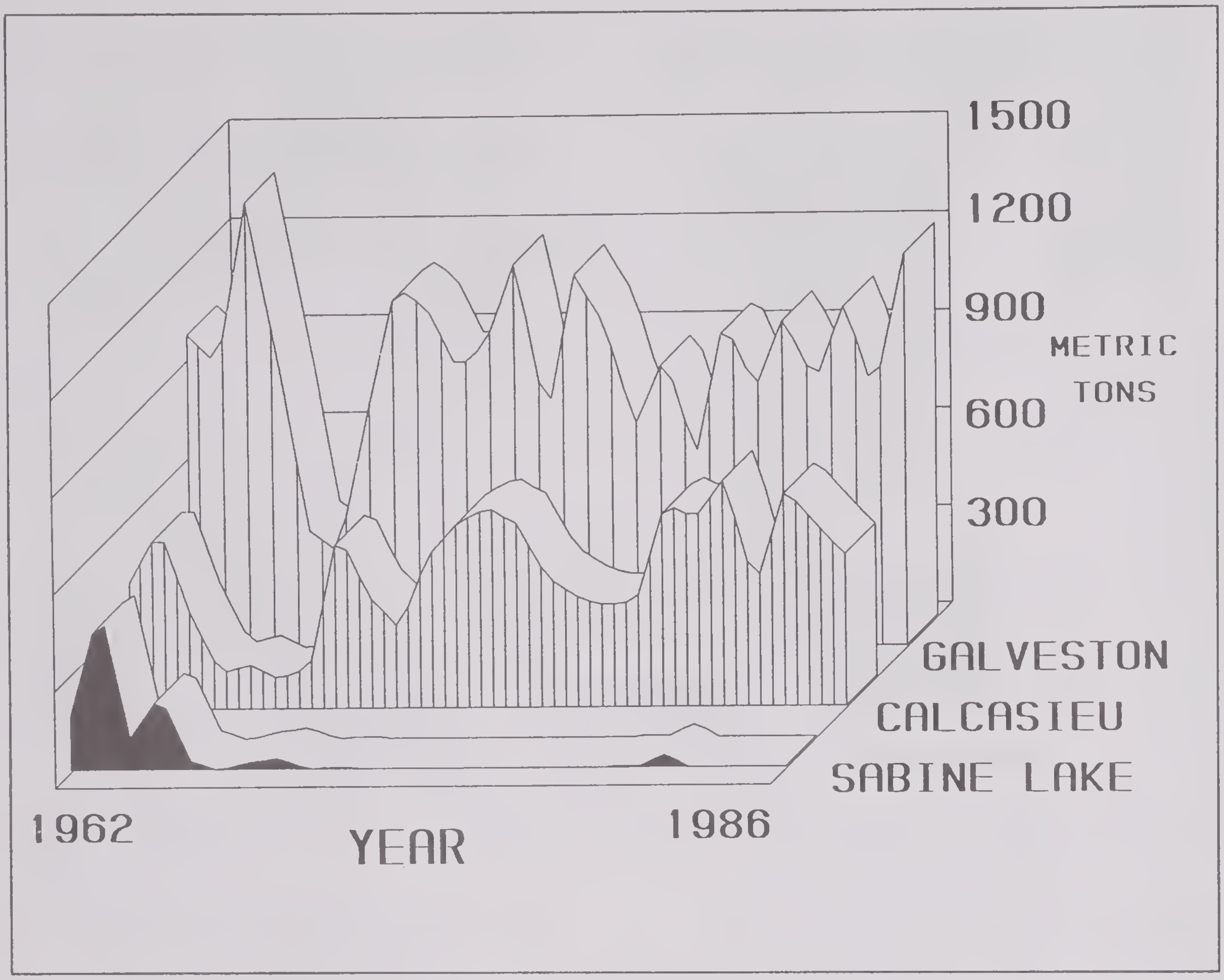

Figure 2.11. White shrimp production in Sabine Lake, Texas (1962-1986) before and after the Sabine and Neches Rivers were dammed in 1966 compared with landings in Galveston Bay and Lake Calcasieu, Louisiana (56).

Habitat Alteration

The linkage between abundance of (and access to) wetlands and system productivity has been discussed. Just where does Galveston Bay fall when habitat protection is mentioned? In 1979, the estuary was surrounded by approximately 715 square kilometers of wetlands (determined from maps in 15). Wetlands losses between surveys in 1956 and 1979, whether natural or due to human activities, have been severe (15). In the Marsh Point area of East Bay, subsidence and petroleum exploration canals led to a 26 percent loss of salt and brackish marsh to open water. Jones Bay, at the northeast end of West Bay, suffered a 37 percent loss of marsh area due to housing development and its location on the edge of one of the two major subsidence cones in the Houston area. At the mouth of the San Jacinto River, subsidence has caused a 42 percent reduction of fresh marshes and swamps. Seagrasses and other submerged vegetation, primarily found in West Bay but never very extensive, have declined precipitously by 95 percent on a baywide basis. Galveston Island itself has lost 37 percent of its wetlands due to housing projects and industrialization (62). For the entire estuary, a net loss of 16 percent of the vegetated wetlands occurred during the period 1956 through 1979. A complete system inventory is needed to determine what has transpired in the last eight years, a period during which Houston experienced a rapid population growth.

Conclusion

Given all the above information, a distillation of the material leads to three important facts to remember concerning the health of the Galveston Bay biota:

- There is a critical dependence of fish and wildlife on wetlands;
- A continued decline in wetlands acreage is foreseen; and
- The timing and amount of fresh water inflow are critical to the biota as we now know it.

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Galveston Bay and the Surrounding Area: Human Uses, Production and Economic Values

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MEG WILSON—The Galveston Bay complex is adjacent to one of the most populated areas in Texas. It ranks first among urbanized areas in the state (1). With a 1980 population of 2,905,353, the Houston Standard Metropolitan Statistical Area (SMSA) ranks second only to the Dallas-Ft. Worth SMSA. Houston is the ninth largest SMSA in the U.S. (2). Of the 16 Standard Consolidated Statistical Areas (SCSA) in the U.S., Houston-Galveston ranks eighth (2).

In 1980 nearly 2.8 million people lived in the four counties surrounding the bay (Chambers, Brazoria, Galveston and Harris), with 2.4 million in Harris county alone (Table 3.1). These four counties account for 75 percent of the population residing within the one-county coastal strata adjacent to the Texas coast, and 20 percent of the total state population. In comparison, 1,466,000 persons (65 percent of the coastal population) lived in the four counties in 1960; this accounted for 15.3 percent of the state population. Population growth will continue until at least the year 2000, when more than four million persons are projected to live in the Texas coastal area (3). At that time, it is projected that the four-county Galveston Bay area will account for 77 percent and 20 percent of the coastal and total state populations, respectively.

Total personal income along the Texas coast is also heavily skewed towards the Galveston Bay area. Of $42 billion in personal income in the coastal counties in Texas, $35.5 billion (83 percent) is accounted for by the four counties surrounding Galveston Bay (Table 3.2).

The purpose of this paper is to provide information on the extent to which Galveston Bay and its adjacent land area are used for various purposes and their respective economic values. In some cases, data are not available to demonstrate the extent of present use; data on level of infrastructure or some other indicator are used as proxies. Use and value are presented as a percentage of total activity for the Texas coast to put Galveston Bay in perspective, and where data are available, changes in Galveston Bay use levels and values over time are presented to understand trends. Finally, some findings regarding demographics and use are compared with those from other estuaries in the United States. In the following paragraphs, information is presented on seven major use categories for the Galveston Bay complex.

Agriculture

In 1982 there were 1,430,626 acres of farm land in the four counties surrounding Galveston Bay (Chambers, Brazoria, Galveston and Harris) or approximately 26 percent of the total farm acreage in the 16 Texas coastal counties. Between 1967 and 1982, there was a decrease of 297,374 acres (21

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Table 3.1. Distribution of Population Along Texas Coast and Percent Accounted for by the Galveston Bay Complex for the Years 1960, 1970, 1980, 1990 and 2000.					
	1960[a]	**1970[b]**	**1980[c]**	**1990[d]**	**2000[d]**
Jefferson	245,659	244,937	250,938	266,664	272,346
Chambers	10,379	12,187	18,538	21,310	22,955
Harris	1,243,158	1,741,908	2,409,547	3,078,356	3,584,883
Galveston	140,364	169,812	195,940	228,833	246,490
Brazoria	72,204	108,312	169,587	206,657	235,848
Matagorda	25,744	27,913	37,828	37,869	34,057
Jackson	14,040	12,975	13,352	14,392	14,330
Calhoun	16,592	17,831	19,574	24,694	28,580
Refugio	10,975	9,494	9,289	9,087	8,309
Aransas	7,006	8,902	14,260	20,012	24,608
San Patricio	45,021	47,288	58,013	66,780	70,685
Nueces	221,573	237,542	268,215	324,410	380,285
Kleburg	30,052	33,173	33,358	37,268	39,501
Kenedy	884	699	534	534	586
Willacy	20,084	15,570	17,495	19,845	20,668
Cameron	151,098	140,368	209,727	270,524	318,384
Total	**2,254,833**	**2,828,911**	**3,726,195**	**4,627,235**	**5,302,515**
Percent of coastal strata contained in four-county area	65.0%	71.8%	75.0%	76.4%	77.1%
Percent of state population contained in four-county area	15.3%	18.2%	19.6%	20.0%	20.1%

Source:
[a]23.
[b]24.
[c]1.
[d]3.

percent) in the four-county area. Commercial fertilizer was used on 283,792 acres in the four counties at a cost of $8,711,000. The market value of agricultural products sold from the four counties in 1982 was $113,747,000, with the vast majority from Harris (grains, nursery products and livestock) and Brazoria counties (grains) (4).

Fisheries

Commercial Fishing

An estimated 425,000 pounds of finfish, with an estimated ex-vessel value of $206,000, were reported as harvested commercially from Galveston Bay in 1986 (Table 3.3). This represents 28 percent of the Texas bay finfish production by weight and 21 percent by value. Galveston Bay also plays a major role in the Texas shellfish industry. More than 30 percent of the shrimp and blue crab harvested commercially from Texas bays are from Galveston Bay. Oysters from Galveston Bay, however, have the largest total ex-vessel value of any shellfish, nearly $7 million (67 percent of the state bay total).

The annual inshore and offshore commercial fish landings (finfish and shellfish) along the Texas coast for 1986 was about 116 million pounds with an ex-vessel value of $246 million (5). Fesenmaier and Jones (6) report an average annual ex-vessel value of $205 million for inshore-offshore commercial fishing for the 1984-1986 period. Of this $205 million, the Galveston Bay complex accounted for

Table 3.2. Distribution of Personal Income During 1981 According to Coastal County, and Percent Accounted for by the Four-County Galveston Bay Complex.

County	Income (in thou.)	Percent
Jefferson	2,709.2	6.4
Chambers	201.7	0.5
Harris	32,414.4	76.0
Galveston	1,450.9	3.4
Brazoria	1,390.4	3.3
Matagorda	267.6	0.6
Jackson	59.4	0.1
Calhoun	220.0	0.5
Refugio	58.6	0.1
Aransas	67.0	0.2
San Patricio	314.6	0.7
Nueces	2,306.3	5.4
Kleburg	196.8	0.5
Kenedy	5.0	<0.1
Willacy	50.8	0.1
Cameron	945.4	2.2
Total	**42,658.1**	**100.1**

Source: 17.

Table 3.3. Estimated Commercial Harvest of Finfish and Shellfish from Galveston Bay During 1986.

	Pounds Harvested	% of all bays total weight	Ex-vessel value	% of all bays ex-vessel value
Finfish	424,495	28	206,491	21
Shellfish				
Shrimp	6,152,860	30	6,839,741	27
Oyster	3,538,808	63	6,951,738	67
Blue crab	3,018,315	32	1,028,097	33

Source: 25.

$63.6 million, or 31 percent (Table 3.4). This activity generated approximately $18 million in personal income. Gross personal income in Texas attributed to commercial fishing in Galveston Bay and supporting sectors resulted in state tax revenues of $2.8 million and taxes paid to local governments statewide of $4.4 million.

The Texas Department of Water Resources (7) reported a much higher value for the Galveston Bay commercial fishery in 1976. In their report, Galveston Bay accounted for $115 million (43 percent) (in 1986 dollars) of the total commercial landings coastwide (Table 3.5).

Sport Fishing

Recreational boat fishermen landed 3.2 million pounds of finfish from Texas bays during 1986. Of the total, more than 1.1 million pounds (35 percent) were landed in Galveston Bay (Table 3.6). This proportion has remained steady for the previous three years. Landings by shore-based fishermen are not available.

Sport fishing expenditures associated with the Galveston Bay estuary account for approximately

Table 3.4. Direct and Total[a] Economic Impacts of the Inshore and Offshore Commercial Fishery in the Galveston Bay Complex (Trinity-San Jacinto Estuary), 1986.

	Landings		Total Inshore		Total Inshore/Offshore	
	Inshore	Inshore/ Offshore	Regional	State	Regional	State
Output (Million $)	12.5	63.6	32.9	41.1	167.6	209.3
Income (Million $)	3.5	18.0	7.3	10.4	37.2	52.7
State Tax Revenues (Million $)	0.1	0.3	[b]	0.6	[b]	2.8
Local Tax Revenues (Million $)	0.1	0.4	[b]	0.9	[b]	4.4

[a]Total = direct, indirect and induced
[b]Data not available

Source: 6.

Table 3.5. Direct and Total[a] Economic Impact of Commercial Fishing, Galveston Bay Complex (Trinity-San Jacinto Estuary), 1976[b].

	Fishing Sector	Total Regional	Total State
Output (Million $)	115.0	244.2	358.0
Income (Million $)	38.3	81.3	98.4
State Tax Revenues (Million $)	0.4	2.3	3.2
Local Tax Revenues (Million $)	0.5	4.0	4.5

[a]Total = direct, indirect and induced
[b]In 1986 dollars

Source: 7.

Table 3.6. Annual Weight of Finfish Landed by Recreational Boat Fishermen from Galveston Bay During 1984, 1985 and 1986.

Year	Galveston Bay	All Texas Bays	% of total weight from Galveston Bay
1983-1984	1,391,100	4,316,900	32
1984-1985	940,700	2,922,000	32

Source: 5.

one-half of all sport fishing expenditures in the Texas coastal bay systems (6). Sport fishing expenditures in the local area surrounding the Galveston Bay estuary during 1986 were over $171 million. Gross Texas business in 1986 resulting from the sport fishing use of Galveston Bay totaled $576.7 million (Table 3.7). An additional $10 million was spent outside the region within Texas. Regional households received an annual income of $104 million from the sport fishing business in the area. Gross personal income in Texas attributed to sport fishing in the Galveston Bay complex was estimated at more than $154 million, resulting in state taxes of $7.8 million and taxes paid to local governments statewide at $13.9 million.

Table 3.7. Direct and Total[a] Economic Impact from Sport Fishing Expenditures, Galveston Bay Complex (Trinity-San Jacinto Estuary), 1986[b].

	Direct[c]		Total	
	Regional	State	Regional	State[d]
Output (Million $)	171.5	181.2	433.2	576.7
Income (Million $)	53.6	66.1	104.0	154.5
State Tax Revenues (Million $)	e	0.8	7.4	7.8
Local Tax Revenues (Million $)	e	2.3	13.1	13.9

[a]Total = direct, indirect and induced
[b]Values in 1986 dollars
[c]Direct impacts for the region and state differ due to the travel expenditure adjustment
[d]Statewide expenditures include the regional impacts
[e]Data not available

Source: 6.

Table 3.8. Direct and Total[a] Economic Impact from Sport Fishing Expenditures, Galveston Bay Complex (Trinity-San Jacinto Estuary), 1976-1977[b].

	Direct[c]		Total	
	Regional	State	Regional	State[d]
Output (Million $)	7.7	7.9	17.7	25.8
Income (Million $)	2.8	3.0	5.2	7.3
State Tax Revenues (Million $)	e	0.1	0.2	0.3
Local Tax Revenues (Million $)	e	1.0	0.3	0.4

[a]Total = direct, indirect and induced
[b]Values in 1986 dollars
[c]Direct impacts for the region and state differ due to the travel expenditure adjustment
[d]Statewide expenditures include the regional impacts
[e]Data not available

Source: 7.

These figures are much higher than those reported by the Texas Department of Water Resources. In 1976, sport fishing expenditures in the Galveston estuary were reported to be nearly $8 million (in 1986 dollars) or about 9 percent of total sport fishing expenditures coastwide (7) (Table 3.8).

Recreation and Tourism

Galveston Bay is used for other recreational activities besides sport fishing by residents in adjacent counties and tourists attracted to the region for business and/or pleasure. These activities include pleasure boating, hunting, swimming, camping, picnicking and sightseeing among others. For these activities, use data are either not available at all or not available specific to Galveston Bay. However, it is possible to approximate the extent of pleasure boating activity through boat registrations and data on boating facilities.

In 1986, there were 103,562 motor boats registered in four adjacent counties. This is 71 percent of the total number of pleasure craft registered in Texas coastal counties, or 24 percent of the motorboats registered statewide (8). Likewise, 38 (46 percent) of the boat ramps administered by the Texas Parks and Wildlife Department on the Texas coast are located in the four counties. This constitutes 27 percent of their boat ramps statewide (8). Between 1976 and 1987, the number of marinas in Galveston Bay more than doubled from 18 to 40, while the number of wet slips grew three-fold from 3066 to 9171 (9). In terms of Galveston Bay's importance to recreational boating in Texas today, Galveston Bay accounts for 30 percent of the total number of marinas on the Texas coast and 63 percent of the total wet slips in commercial marinas. This has grown from a 1976 figure of 27 percent of total marinas and 56 percent of coastal wet slips (Table 3.9).

Visitors participating in sport fishing and other recreational activities (hunting, picnicking, swimming, camping, pleasure boating and sightseeing) in the six estuaries on the Texas coast spent approximately $586 million during 1986 (6). Of this total, $364 million (62 percent) was spent by sport fishermen. Direct expenditures for "other recreation activities" in the Galveston Bay complex were $122.4 million, 55 percent of the total expenditures for this category for all bay systems on the Texas coast (Table 3.10). Gross Texas business resulting from tourism and recreational uses of the Galveston Bay complex amounted to $425.2 million. Gross personal income in Texas attributed to "other recreational activities" in the Galveston Bay complex and supporting sectors was estimated at $113.3 million, state taxes at $5.7 million and taxes paid to local governments statewide at $10.1 million.

Comparisons with data collected by the Texas Department of Water Resources (7) are not possible since the "other recreation" category was not included previously.

Petroleum, Chemicals and Other Manufacturing

The four-county study area surrounding Galveston Bay contained 85 percent (3,989) of the manufacturing establishments in the 16 Texas coastal counties (1). Although there were approximately one-half as many establishments in 1963 (2,221), they nevertheless constituted 78 percent of the total in the coastal counties at that time. In 1982, the four counties accounted for about 22 percent of the total number of manufacturing establishments in Texas (10).

Despite the popular perception that petroleum is Houston's largest and most valuable industry, the chemical and allied products industry ranks first in the Houston area in terms of value added by manufacturing ($5.0 billion) (10). This constitutes about 30 percent of the total value added by manufacturing in the Houston-Galveston SCSA (Galveston-Texas City, TX SMSA; Houston, TX SMSA). There are 301 establishments in the area with a total of 36,100 employees and a payroll of $1.1 billion. The vast majority (89 percent) of the establishments in the four-county area are located in Harris County.

Nearly one-half of the total chemical production in the U.S. takes place in the Houston area. More than 500 chemicals are produced there, including 55 percent and 34 percent of the total polypropylene and polyethylene production, respectively, in the U.S. Furthermore, 46 percent of the total U.S. production of ethylene and propylene takes place in Houston (11).

Thirty percent of the U.S. petroleum industry is located in the area adjacent to the Galveston Bay complex (12). In the Houston area the petroleum and coal products industry ranks third in terms of value added by manufacturing ($2.2 billion) (10). This is about 13 percent of the total value added by manufacturing in the Houston-Galveston SCSA. There are 69 establishments in the SCSA with a total

Table 3.9. Number of Marinas and Wet Slips in Galveston Bay and for the Texas Coast, 1976-1987.

	Galveston Bay		Galveston Bay as % of Total Coastal		Coastal Texas	
	# of Marinas	Wet Slips	Slips	Marinas	# of Marinas	Wet Slips
1976	18	3,066	56.1	27.3	66	5,469
1981	21	4,151	58.1	25.6	82	7,150
1985	26	6,579	61.5	28.9	90	10,706
1987	40	9,171	62.9	29.9	134	14,573

Source: 26,27,28.

Table 3.10. Direct and Total[a] Economic Impact from Other Recreation[b] Expenditures, Galveston Bay Complex (Trinity-San Jacinto Estuary), 1986[c]

	Direct[d]		Total	
	Regional	State	Regional	State[e]
Output (Million $)	122.4	131.8	311.0	425.2
Income (Million $)	38.2	48.5	74.5	113.3
State Tax Revenues (Million $)	[f]	0.6	5.3	5.7
Local Tax Revenues (Million $)	[f]	1.6	9.5	10.1

[a]Total = direct, indirect and induced
[b]Activities include hunting, picnicking, swimming, camping, pleasure boating and sightseeing
[c]Values in 1986 dollars
[d]Direct impacts for the region and state differ due to the travel expenditure adjustment
[e]Statewide expenditures include the regional impacts
[f]Data not available

Source: 6.

of 16,900 employees and a payroll of $557 million. The vast majority (81 percent) of these establishments in the four county area are located in Harris County.

Level of infrastructure is an indicator of the extent to which the petroleum industry along the Texas coast is focused on Galveston Bay. Of 31 oil refineries on the Texas coast, 12 (39 percent) are located in the four-county study area, representing 44 percent of the coastwide oil refinery design capacity (13). This is approximately 17 percent of the total oil refinery design capacity in the Gulf of Mexico. Of the 74 gas processing plants on the Texas coast, 22 (30 percent) are located in the four counties. Thirty-two percent of the gas processing plant design capacity along the Texas coast is located in the four county area (13). Of the 38 pipelines originating from either state or outer continental shelf (OCS) waters along the Texas coast, 16 (42 percent) make landfall in the four county area. The vast majority of pipelines from state waters make landfall in Brazoria County while the vast majority from OCS waters make landfall in Galveston County. Gas pipelines in these areas range in diameter from 6" to 24," with oil pipelines being 4" to 14" in diameter (13).

Wastewater Discharge

More than one-half (51 percent) of the 3756 wastewater permittees in the state of Texas in 1987 are

Table 3.11. Number of Wastewater Permittees in Galveston Bay Watershed.

Area	Number of Permits[a]		
Trinity Basin (above Lake Livingston Dam)	519		
San Jacinto Basin (above Lake Houston Dam)	262		
Galveston Bay (below Livingston and Houston Dams)	1,151		(719)[b]
Domestic		674	(484)
Industrial		477	(235)
Total Galveston Bay Watershed	1,932		
Total Permittees in Texas	3,756		

[a]These include both active and inactive permits. "No discharge" permits are not included.
[b]These include only discharging active permittees.

Source: 14.

located in the Galveston Bay watershed (Table 3.11). About 31 percent are in the immediate vicinity of the Bay (below the Lake Livingston and Lake Houston Dams). Not all of these are active permits involving wastewater discharge. In the vicinity of the Bay are 484 active domestic permittees discharging 1.5 billion gallons/day and 235 active industrial permittees discharging 36.5 billion gallons/day. In 1970 there were 139 self-reporting domestic permittees and 160 self-reporting industrial permittees in the vicinity of the Bay (comparable area to that used in 1987). Increases in the number of domestic and industrial wastewater permittees between 1970 and 1987 were 248 percent and 47 percent, respectively (14). No data regarding volume of wastewater discharged in the study area were available for 1970.

Transportation and Navigation

Nationally, the Port of Houston is the third largest in the contiguous 48 states in terms of total shipping tonnage. Access to the Port is provided from Galveston Bay westward along the 50 mile-long Houston Ship Channel to the turning basin in Houston's Central Business District.

The Port of Houston is the leading port in Texas in terms of 1986 shipping tonnage (102 million tons), more than twice as much as the next competitor (Port of Corpus Christi). The Port of Galveston ranks seventh among eleven Texas ports with 8.2 million tons. Together, these two ports account for approximately 43 percent of the total tonnage along the Texas coast (15). In 1986, 4817 ocean-going vessels (import or export) docked at the Port of Houston while 430 docked at the Port of Galveston (15). Total revenue generated by the Port of Houston was $3.0 billion in 1986 (16), nearly six times that generated by the Port of Galveston (Table 3.12). Two commodity groups (petroleum and liquid bulk) accounted for a majority of the total 1986 revenue in the Port of Houston. Grain accounted for almost one-half the total revenue and tonnage for the Port of Galveston. No estimates of the economic impacts of revenue generated by the ports on the region and state are available. Martin O'Connell Associates (16) argue that personal income is a better measure of the ports' economic value to the state and local economies than total revenue since monetary impact is specific to the state.

The Ports of Houston and Galveston are major sources of income and employment for the region. Estimated total employment impacts to regional economies were 6,993 and 47,781 full time equivalents for the Ports of Galveston and Houston, respectively. In 1981 gross personal income in the region attributed to the Ports of Galveston and Houston was $336 million and $1.6 billion, respectively.

Table 3.12. Direct and Total[a] Economic Impact from the Ports of Houston, 1986 and Galveston 1981[b].

	Direct		Total	
	Port of Galveston	Port of Houston	Port of Galveston	Port of Houston
Revenue (Million $)	638	2,976	N/A	N/A
Employment (Man-years)	4,138	28,650	6,993[c]	47,781
Income (Million $)	184	712	405[d]	1,567

[a]Total = direct and indirect
[b]Values in 1986 dollars
[c]Secondary employment derived using a 1.69 employment multiplier for waterborne transportation (TDWR, 1983)
[d]Secondary income derived using a 2.2 income multiplier recommended by the U.S. Department of Commerce Maritime Administration (1980)

Source:
1. Port of Galveston figures were derived from U.S. Army Corps of Engineers, Galveston District, 1987.
2. Port of Houston figures from 16.

Other Uses

Housing

The four counties surrounding Galveston Bay contained 1,135,271 (77 percent) of the housing units in the 16 Texas coastal counties in 1980 (17). This pattern was much the same in 1960 when these counties contained 487,076 (67 percent) of the housing units coastwide (18). According to recent data collected by the U.S. Bureau of the Census, Chambers, Brazoria, Galveston and Harris counties accounted for 66 percent of the building permits issued for single and multi-unit housing on the Texas coast between January-October 1987 (19).

Military

One of eight new Homeport naval installations nationwide will be developed in Galveston beginning in 1988. Eventually, two frigates, two mine sweepers and one patrol boat will be based there. Federal and local investment in facility development will be approximately $33 million and $3 million, respectively. Direct expenditures for ship repairs and related business in the local area will be an estimated $11 million with a total economic impact on the region of $25 million. The payroll for the estimated 650 persons (ship and land-based personnel) associated with the base will be approximately $16.5 million (20).

Galveston Bay in National Perspective

When Galveston Bay is compared with thirteen other estuarine areas studied by Nixon (21), it ranks eighth in watershed area and fourth in surface area (behind Chesapeake Bay, Long Island Sound and Delaware Bay, respectively) (Table 3.13). Of 92 estuarine areas in the U.S., only 25 had a larger total drainage area than Galveston Bay (22). In terms of number of square kilometers devoted to industrial activity (light to heavy manufacturing) among the 92 estuarine areas studied, the Galveston Bay area (24) ranked third behind San Francisco Bay (337) and San Pedro Bay (249) (7). Although the Galveston Bay area was ranked among the top six estuarine areas studied by Nixon in terms of 1980 population levels (Figure 3.1), population density is not high due to the extensive acreage in the four counties adjacent to the Bay (Table 3.14). It was impossible to make comparisons between bay systems regarding the economic value of various uses due to the lack of available standardized data.

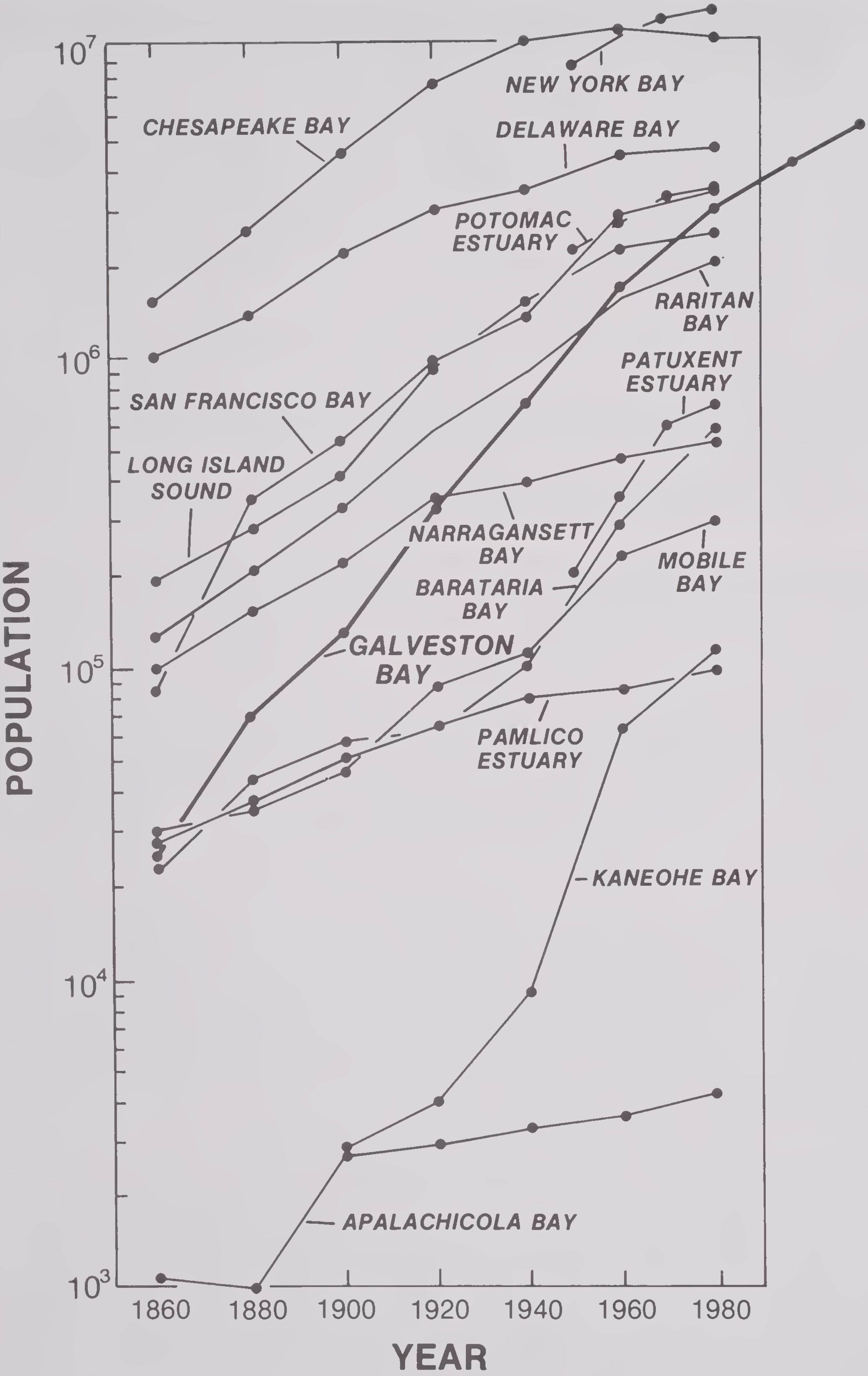

Figure 3.1. Human population adjacent to selected estuarine study areas.

Source—
All data except for Galveston Bay were derived from 21. Data for Galveston Bay counties are from 29.

Table 3.13. Approximate Physical Dimensions of Selected Estuarine Study Areas.

Watershed	Surface Area, KM^2	Ranking	Area, KM^2	Ranking
Galveston Bay	32,510	8	1,600	4
Narragansett Bay	4,800	10	285	12
Long Island Sound	42,000	4	3,200	2
New York Bay	38,000	5	390	10
Delaware Bay[a]	33,000	7	1,942	3
Chesapeake Bay[b]	110,000	2	11,500	1
Patuxent Estuary	2,200	12	122	15
Potomic Estuary	38,000	5	1,251	5
Pamlico Estuary	11,000	9	305	11
Apalachicola Bay	44,000	3	210	13
Mobile Bay			1,070	7
Barataria Bay	4,000	11	176	14
San Francisco Bay[c]	160,000	1	1,240	6
Suisun Bay plus San Pablo Bay			445	9
South Bay			490	8
Kanaohe Bay	97	13	32	16

[a]Below Smyrna River
[b]Including tributaries
[c]Including mud flats

Source: All data except for Galveston Bay were derived from 21. Data for Galveston Bay are from 7.

Table 3.14. Population Density (People/Acre) Surrounding Estuarine Study Areas.

	Population Density	Ranking
Galveston Bay	1.0	9
Narragansett Bay	1.5	3
Long Island Sound	1.1	8
New York Bay	3.2	2
Raritan Bay	1.5	3
Delaware Bay	0.3	11
Chesapeake Bay	1.2	7
Patuxent Estuary	0.4	10
Potomic Estuary	0.1	13
Pamlico Estuary	<0.1	14
Apalachicola Bay	0.3	11
Mobile Bay	1.5	3
Barataria Bay	2.3	3
San Francisco Bay	4.6	1

Source: All data except for Galveston Bay were derived from 21. Data for Galveston Bay are from 1, 17.

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Issues and Information Needs

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R.W. McFARLANE—Galveston Bay today is a sea of controversy, as proponents of development and protectors of natural resources challenge opposing claims of no-effect and environmental calamity. Any large, heavily industrialized city adjacent to an estuary will eventually impinge on the water quality of the waterway. A review of existing conditions and predictable changes in water quality of the Galveston Bay system must acknowledge that everything is connected to everything else, and it is impossible to do merely one thing. A change in one factor influencing the bay will automatically produce changes in other facets of bay dynamics.

Population and industrial growth always produce byproducts, some of which are waste materials, and everything has to go someplace. The law of gravity ensures that material transport is downhill, and Galveston Bay will be a temporary repository for these waste materials as they inexorably move toward the Gulf of Mexico and beyond. Even substances that are removed by waste treatment procedures have not disappeared. It can be assumed that all waste products released into the environment may be **transported** by natural processes to places other than the point of release, and that many will be **transformed** into other chemical or physical forms during this process. Many of the chemicals will be incorporated into living organisms by the process of **bioaccumulation**, and some will be **biomagnified** to higher concentrations with each transfer along the food chain. As these chemicals interact with each other in the environment, they are likely to produce **synergistic effects** greater than any one of them could invoke acting alone.

Finally, we must acknowledge that everything is constantly changing. Even if all development and population growth were to cease today, the components of the Galveston Bay ecosystem will continue to change. Our challenge is to sort out the effects of changes induced by man and identify those that need to be modified and minimized. We must carefully weigh the benefits of development projects against the costs to the commonweal. The continued health and productivity of Galveston Bay are in the best interests of everyone.

The focus of our immediate concern is the ability of Galveston Bay to sustain, or enhance, its present commercial and sport fishery productivity and recreational value while facing numerous development projects (Table 4.1), underway or proposed, that can affect water quality. Some of these developments are large federal projects with potentially significant impacts. Others are small shoreline modifications proposed by private developers that, cumulatively, significantly reduce the acreage of shoreline wetland vegetation and productive bay bottom. The common thread that links all of them is the substantial population growth that the area has experienced. Population and industrial growth have increased the demand for natural resources and disposition of waste materials.

Issues

The critical issues associated with these projects are (1) **water quality** changes in the bay and its tributaries, which transport nutrients and both treated and untreated wastewater to the bay; (2)

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[1]R.W. McFarlane represents McFarlane & Associates; T.J. Bright and M. Hightower, Texas Sea Grant Program; B.W. Cain and A. Mueller, U.S. Fish and Wildlife Service; J. Kendall and J.W. Kolb, Texas Water Commission; P. Sheridan, National Marine Fisheries Service; C.B. Smith, Texas General Land Office; E.G. Wermund, Bureau of Economic Geology, The University of Texas at Austin; T.E. Whitledge, The University of Texas at Austin Marine Science Institute.

Table 4.1. Existing and Proposed Development Projects Affecting Galveston Bay.

Navigation Projects
Texas City Channel Enlargement
Galveston Channel Enlargement
Houston Channel Enlargement
Liberty Channel Enlargement
Gulf Intracoastal Waterway Enlargement
Galveston Home Port
Water Development Projects
New Reservoirs
Wallisville Lake
Bedias
Lake Creek
Tennessee Colony
Existing Reservoirs — Interbasin Transfer of Waters
Luce Bayou (Trinity River to San Jacinto basin)
Toledo Bend (Sabine River to San Jacinto basin)
Flood Control Projects
Buffalo Bayou and Tributaries
San Jacinto River and Tributaries
Shoreline Development Projects
Industrial Shoreline Development
Resource Extraction, Bay and Onshore
Waterfront Housing Development
Galveston Island Causeway
Private Property Development

reductions in **freshwater inflow** to the bay system and its associated wetlands, and subsequent changes in bay salinity; (3) enlargement and maintenance of **navigation channels** as regards dredged material disposal, increased turbidity, resuspension of toxic or hazardous chemicals, and changes in bay salinity profiles; (4) **loss of contiguous wetlands** due to subsidence, erosion or shoreline development; (5) **energy production** in a bay environment; (6) comprehensive assessment of **cumulative impacts**; and (7) **ecosystem interconnections**. The impact of possible changes on salinity, productivity, eutrophication, and public health will be discussed below. It may be necessary to consider changes and developments within the entire bay watershed (see Appendix I), 360 miles long and as much as 100 miles wide, inhabited by nearly 6 million people. The important questions to ask are these. How much has past development influenced the bay? How will current and proposed projects affect the bay? What will be the cumulative impact on the bay of existing projects functioning at their design capacity plus the proposed future projects?

Water Quality

Water quality is affected by natural variations in chemical concentrations within a water body, the accidental or deliberate discharge of natural or synthetic chemicals, thermal discharges, and the distribution and abundance of pathogens. The diversion of water within a drainage for human purposes and the subsequent return of much of this water as wastewater effluent affects the minerals and nutrients transported by the water before and after human use. Suspended and dissolved solids are removed by water treatment before distribution to consumers, potentially affecting the concentrations of micronutrients that would have reached the bay. Treated wastewaters contribute substantial amounts of macronutrients to the bay. A certain amount of nutrient enhancement will stimulate bay productivity; an excessive amount could lead to eutrophication and reduced productivity, at least in those products most useful to man.

The distribution of total organic carbon (TOC) is positively correlated with the percentage of mud

Table 4.2. Distribution of Total Organic Carbon in Galveston Bay.

Location	High Values (percent)
West Bay	1.6
East Bay	1.8
Galveston Bay	1.9
Trinity Bay	2.4
Buffalo Bayou/ Houston Ship Channel	3.9
Offatt Bayou	4.0
Galveston Channel	5.7

Source: (1)

in bottom sediments. Highest concentrations of TOC occur in bay-center muds, and lowest in bay-margin sands. Upper bay concentrations (Trinity Bay) are greater than those found in the lower bays (West Bay, East Bay), as shown in Table 4.2. The highest concentrations of TOC, however, occur in channels characterized by deeper-water, wave-protected, and oxygen-deficient bottom sediments that locally serve as sinks for the accumulation of organic-rich muds (1). High concentrations are widely distributed in Trinity Bay, particularly near its head. The Trinity River and bay-head delta are probably the primary sources of the carbon. The Trinity River valley contains floodplain swamps and marshes that export organic carbon during floods. There is widespread concern that construction of the Wallisville dam near the mouth of the Trinity River will affect the transport of vital nutrients to the bay. More than 95 percent of carbon, nitrogen and phosphorus input to Galveston Bay arrives with freshwater inflow (2). The Trinity River alone provides half of all freshwater inflow to Galveston Bay.

Eutrophication is an excess of dissolved nutrient concentrations in a body of water that produces a noticeable change in water quality that may range from simple discoloration to catastrophic events, such as fish kills. A whole host of intermediate eutrophication effects, such as changes in species composition of food organisms or "dead water" depleted of oxygen, may result. Historically, Galveston Bay has contained elevated concentrations of nutrients derived from discharges and non-point sources (3). Concentrations greater than National Academy of Science guidelines were accompanied by severe oxygen depletion in the Houston Ship Channel (84 percent), Galveston Bay (12 percent), Trinity Bay (4 percent), and West Bay (4 percent of the time), when judged against a 5 mg/1 criterion (4). Light limitation from silt or suspended sediment may hamper plant growth in the vicinity of nutrient inputs. Freshwater inflows are responsible for the major portions of nutrient inputs to Galveston Bay (5) and light limitation apparently reduces the importance of phytoplankton in regions of the estuary that are turbid.

Recent evaluation of nutrient loading by the Texas Water Commission (6) clearly showed a reduction of nutrient loading of nitrogen and phosphorus from 1976 to 1983, compared to the years 1969 to 1975. The mean concentration of ammonia-N decreased from 0.154 to 0.079 mg/1, and orthophosphorus decreased from 0.463 to 0.293 mg/1. BOD reductions were also observed that produced high oxygen concentrations in previously impacted areas. Even though Galveston Bay waters have recently had smaller nutrient concentrations than previously measured in the 60s and 70s, their deleterious effects have not been eliminated since many non-point sources are not controlled (e.g., agricultural fertilization). Accidental or deliberate discharges are also often significant in small areas for short periods, as when sewage and sludge released into White Oak Bayou killed thousands of fish by oxygen depletion in September 1987.

Sediments in waterways near industrial facilities generally have levels of **heavy metals** (arsenic, cadmium, copper, lead, mercury, nickel, tin and zinc) that exceed background levels for that waterway. Resuspension and redistribution of these contaminated sediments by ship traffic, tidal or wave action, and dredging operations are reasons to be concerned about the impact of heavy metals on the natural resources in Galveston Bay. Many of these heavy metals are bioaccumulated from the sediment by benthic infauna and epifaunas and some plant species. A number of factors, such as pH,

Table 4.3. Heavy Metal Concentrations in Galveston Bay Sediments.

Metal	Proposed EPA Screening Level (ppm)	Bay Sediments (muds, ppm) mean	Bay high	Buffalo Bayou/ Houston Ship Channel high
Chromium (total)	100	55	120	150
Copper	50	28	130	160
Lead	50	34	140	260
Nickel	50	26	113	
Zinc	75	89	275	590

Source: 1.

the chemical form of the metal, other chemicals or chelating agents, and the redox potential of the sediment, will influence the amount of bioaccumulation that will occur.

Local concentrations of chromium, copper, lead, nickel and zinc can exceed the proposed screening levels for dredged-sediment disposal established by the U.S. Environmental Protection Agency (Table 4.3). Abnormally high trace metal concentrations in sediments at many locations probably result from anthropogenic contributions. Highest concentrations were found in channel sediments, such as the Buffalo Bayou/Houston Ship Channel and Texas City Channel, where industrial and municipal discharges have been reported and widely publicized previously (1). A probable source of trace metals in Trinity Bay and East Bay is the Trinity River, where higher than normal levels of heavy metal particulates have been reported in river water. Simulated flow patterns indicate that predominate net flow is from Trinity Bay around Smith Point into East Bay during several months of the year.

Other, less obvious, sources of contaminants also impact the bay. Copper, for example, is a potent algacide and one very soluble form in estuarine water can have an impact on the phytoplankton community. Copper and tributyltin are used in antifouling paints on ships, bulkheads and submerged structures. Tributyltin leaches from these paints and is so toxic to shellfish that Virginia, Maryland and several European countries have banned this compound. Concentrations in water as low as 1 part per trillion can adversely affect the reproductive cycle of oysters. Hundreds of fishermen and pleasure boaters on Galveston Bay are now painting their boats with the repellent. Oysters recently collected from four locations in Galveston Bay contained 120 to 1,000 parts per billion tributyltin.

Hundreds of **petroleum compounds** (aliphatic and aromatic hydrocarbons) are discharged, dumped or spilled each day into the Galveston Bay system. These petroleum compounds vary in their toxicity to bottom-dwelling organisms and juvenile stages of shellfish and finfish. Generally, these compounds do not cause visible fish kills, but they are likely to induce liver damage and promote tumor growth in fish. There are more than 200 oil and gas wells in or near Galveston Bay that produce up to 8 barrels of saltwater for each barrel of oil. This wastewater (brine or produced water), discharged into the bay system, is heavily contaminated with water soluble fractions of oil as well as small droplets of crude oil. More than 1 million barrels of produced water are discharged per day. At the permitted level of 20 ppm oil, there is a minimum of 20 barrels of oil per day being discharged into the bay system. These oil droplets generally get bound to sediment particles in the water and settle into the sediment layer. Benthic organisms are excluded from these discharge points in all directions for up to 50 meters. Petroleum hydrocarbons can be accumulated by living organisms but biomagnification is rare. These hydrocarbons are known to be metabolized in the liver and form reactive intermediate compounds that are carcinogenic and also disrupt the mixed-function oxidase systems in vertebrates. Reduced production and survivability is the end result of chronic exposure to petroleum hydrocarbons.

Sediments in many shellfish and finfish nursery areas also contain **industrial contaminants**, for example, petroleum waste hydrocarbons such as chlorinated phenols, chlorinated styrenes, phthalate esters, and degreasing solvents. These chemical compounds are potent biocides, long-lasting in

Table 4.4. Number of Wastewater Permittees in Galveston Bay Watershed.

Area	Number of Permits
Trinity Basin (above Lake Livingston Dam)	519
San Jacinto Basin (above Lake Houston Dam)	262
Galveston Bay (below Livingston and Houston Dams)	1,151
Total Galveston Bay Watershed	1,932
Total Permittees in Texas	3,756

sediments, and lipophilic. Lipophilicity implies that the compound can be stored in fat tissues and transferred throughout food chains.

Galveston Bay receives runoff from large agricultural and municipal areas that may contain **pesticides**. Fields used for rice, soybean and sorghum production regularly are sprayed with herbicides and organophosphorus pesticides. Rice farming procedures typically keep the rice flooded during the growing season, which enhances runoff during these months. Mosquito abatement programs along the shoreline of Galveston Bay are another source of organophosphorus insecticides. These programs are usually implemented during the spring and summer months, coinciding with the entrance of juvenile crabs, shrimp and fish into the marshes. Most organophosphates are extremely toxic to juvenile stages of aquatic organisms. A third source of pesticides entering the bay is runoff from urban areas. Tons of these chemicals are applied by professional lawn care services, pest control services, and individual landowners. Herbicides and insecticides are applied to gardens, flower beds and drainage ditches. Chlordane is used as a termiticide around residences. Texas Department of Agriculture data indicate that residential runoff transports more pesticides into rivers than farmland.

There are 3,756 permitted wastewater discharge outfalls in Texas. Fifty-one percent (1,932) of them discharge into the Galveston Bay watershed (Table 4.4). Thirty-one percent (1,151) discharge in the immediate vicinity of the bay. The chemical and biological oxygen demands of wastewater effluents and untreated discharges into tributaries and the Houston Ship Channel can drastically lower or eliminate dissolved oxygen concentrations and negatively impact fishes and bottom-dwelling organisms in particular. In addition to the chronic exposure and the continuous or intermittent discharge of contaminants, bay inhabitants are also subjected to episodic petroleum and chemical spills. Segments of a number of bay tributary streams have been designated as "unfishable, unswimmable." Bacterial contaminants from sewage treatment plants and urban runoff have frequently closed down oyster harvesting. Approximately 51 percent of the bay is permanently closed to shellfish harvesting. Toxicants and carcinogens potentially can be introduced into human food chains.

Has past development and waste disposal influenced the biota of Galveston Bay? The issue is difficult to resolve with certainty. As seen in Table 4.4, the species richness of benthic macroinvertebrates varies considerably in different segments of the bay. West Bay exhibits the greatest diversity. Lower Galveston Bay has a richer biota than upper Galveston Bay. The fauna of East Bay seems surprisingly low. Trinity Bay, which experiences the lowest salinity and greatest fluctuations in environmental conditions, appears to be a naturally stressed community. One clam, *Rangia cuneata*, was considered to be a dominant species in Trinity Bay in the early 1970s but appears to have disappeared from many areas, although dead shells occur in all bays (1). Neither polychaetes nor mollusks live in the San Jacinto River or Houston Ship Channel; one crustacean persists in the ship channel.

Information Needs

There are many unresolved questions regarding biogeochemical cycling in Galveston Bay. What are the concentrations and locations of arsenic, cadmium, mercury, selenium and toxic organics that have yet to be measured? Does the concentration and distribution of pollutants change over time? What is the extent of heavy metal contamination in nursery areas receiving urban runoff, industrial

runoff and anti-fouling paint (tributyltin) from marinas? What is the extent of heavy metal contamination in nursery areas by discharge of oil production water? What are the effects of production water on larval stages of crabs, shrimps, oysters and fishes? What are the impacts of production water discharged on wintering waterfowl food items? What is the composition of non-point runoff from agricultural areas? How are contaminants partitioned in the nursery areas? What is the extent of contamination from maintenance dredged material put in confined disposal areas that drain into the bay? What are the dynamics of contaminants in dredged spoil disposal areas as they dry out and then receive precipitation? What is the extent of contaminant remobilization caused by dredging and other bottom disturbances? What are the transfer coefficients for the uptake of sediment contaminants by the biota? How are toxic contaminants degraded in sediment and water? What are the effects of toxicants on endocrinology and reproduction? What are past, current and projected petroleum and chemical spill rates? What were the environmental consequences of past spills? What are the biological effects of eutrophic and hypoxic events? What are current nutrient levels in the bay, at what point would nutrients become excessive, and is this likely to occur in the near future? Do anoxic conditions reach the bay itself? Are there any temporary circumstances that extend the anoxic zone? What is the near-future prognosis regarding bacterial contamination —improvement, deterioration, no change? Would the proposed increase in dredging activity produce a real threat to human health? Do any thermal effluent outfalls constitute a public hazard regarding thermophilic pathogens? Are toxicant levels in human food species a threat to human health?

How important are nutrients in freshwater inflow to the maintenance of our estuaries as we know them today? If nutrients in the freshwater were reduced by a factor of 10, would the resultant effect be linear or non-linear? Would plant growth be reduced enough to affect the feeding of animal populations?? What is the relative importance of in-situ regeneration of nutrients compared to inputs to such shallow estuaries? How do the roles of point and non-point sources compare? Do non-point sources provide different chemical species than point sources? Does a smaller yet highly impacted region around a point source produce a mini-environment of eutrophication with more lethal effects on plant or animal life than non-point sources? What is the short-term temporal behavior of nutrient species that influence primary production processes? Do nutrients display diurnal behavior related to other biological processes, like denitrification, nitrification or decomposition? Are microalgae and phytoplankton species nutrient-limited in Galveston Bay, or do other factors control their growth?

Freshwater Inflow

Galveston Bay is connected to the Gulf of Mexico through two natural entrances, Bolivar Roads and San Luis Pass, and man-made Rollover Pass. Without freshwater input, tidal action would produce equal salinities in both bay and gulf, 35 parts per thousand (ppt, or 3.5 percent) salt. The amount of precipitation that falls on the bay exceeds the volume of water that evaporates from the bay surface by 6 inches, and precipitation accounts for 14 percent of all freshwater that reaches the bay. Thus, precipitation alone would lower bay salinity but an equal amount of water enters from the San Jacinto River, 25 percent of the input drains from the surrounding shoreline, and 48 percent of all freshwater inflow enters from the Trinity River alone (see Appendix I). The average amount of freshwater that enters the bay each year is sufficient to totally replace the volume of water in the bay more than four times.

The salinity gradient in Galveston Bay is highly dynamic, responding to brief environmental changes, such as heavy precipitation events and frontal passages, or extended changes, such as droughts. Passage of a cold front, accompanied by strong northerly winds, has dropped surface salinity at Bolivar Roads from 18 ppt to 0.5 ppt as water was pushed out of the bay, and rebounded to 25 ppt as gulf waters flooded back in, all within 29 hours (7). Although the bay system is shallow throughout, vertical salinity gradients are common, particularly in the navigation channels. Differences as great as 5 ppt can occur in water only 3 feet deep, or 15 ppt in the 40-foot deep channel (8). The efficacy of two-dimensional salinity modeling is questioned when the model fails to predict salinities as high as historical records. Other calculations have predicted that salinities could reach 28 ppt in Trinity Bay when authorized water rights are fully exploited during periods of low Trinity River flow. Salinity increases of this magnitude could seriously affect oyster productivity.

Information Needs

How will changes in salinity affect the distribution of living organisms in the secondary bays (Trinity, East, West)? Will increased salinities permit the persistence of oyster pathogens and predators, thus reducing oyster productivity? How will full utilization of authorized water yields for

Lake Livingston and Wallisville Lake affect salinity in Trinity Bay? If large volumes of water are transferred from Toledo Bend Reservoir and the Sabine River to the San Jacinto River drainage area as municipal and industrial water for Houston, how will the increased flow of wastewater discharge affect the bay? Would a three-dimensional salinity model more accurately portray future salinity gradients; if so, would the difference between model outputs justify the substantial investment of time and funds required to develop and verify the three-dimensional model?

Navigation Channels

Galveston Bay is a drowned river valley that has nearly filled with sediment from the Trinity and San Jacinto Rivers and smaller tributaries. Averaging only 7 feet in depth, bottom sediments are highly susceptible to wind-driven wave action and shrimp trawling that increase turbidity. Current ship channel maintenance dredging, and proposed channel enlargement and subsequent maintenance dredging, threaten to substantially increase turbidity over broad areas simultaneously. Turbidity decreases the depth to which sunlight may penetrate the water and therefore may decrease the primary productivity that supports much of the food web.

Two facts are certain. Dredging will continue to occur if Texas waterways are to remain open. Secondly, economic and environmental decisions relevant to dredge spoil disposal are currently being made without an adequate data base regarding the optimum ratios between habitats, i.e., emergent marsh areas, submerged grass beds, shallow-water and deep-water habitat categories. Historically, state and federal regulatory agencies have required that dredge spoil material be placed either in approved disposal sites at or above mean high water. In the Galveston Bay system, erosion and subsidence has resulted in the conversion of upland habitat into submerged habitat and the conversion of shallow-water habitat into deep-water habitat. Shallow-water habitats are known to be more productive than deeper waters. It may be beneficial to place clean dredged material into the bay system to convert deep-water areas into more productive shallow-water habitat and perhaps achieve a more balanced ecosystem. Conversely, the current practice of placing dredged material above mean high water may need to be continued.

Information Need

A comprehensive habitat analysis needs to be conducted to ascertain the historical versus present ratio of the various habitat categories in terms of acreage and productivity, i.e. emergent marsh areas, submerged grass beds, shallow-water and deep-water habitats, etc. An analysis of this sort could provide data that would be beneficial from both an environmental and economic perspective. What will be the effect of nearly doubling the ship channel cross section, from the existing 40 x 400-foot (16,000 square feet) to the proposed 50 x 600-foot (30,000 square feet) section, on bay salinity and flushing? What will a new 12-foot deep channel across Trinity Bay do to bay salinity? (See Appendix I.) What is the margin of error on the salinity model? What will be the effects of resuspending sediment contaminants?

Loss of Shoreline Uplands and Wetlands

The quantification of loss, or gain, of land caused by natural processes and human activities about Galveston Bay is a principal issue. The loss includes both uplands and wetlands. Land that is eroded returns to the bay and contributes to other principal issues, such as the geochemistry of the bay floor and sediment dynamics. While property losses measured in real estate values are an immediate concern to local citizens, the land lost to the natural system over many years provides better estimates of past and future losses. Shoreline monitoring of the Galveston-Trinity Bay System has demonstrated a shoreline retreat of 2.2 feet per year landward between 1850 and 1982, causing a loss of 8,000 acres of land (9). Shoreline retreat has increased from 1.8 feet per year before 1930 to 2.4 feet per year since then.

The principal natural processes that determine shoreline position are (1) changes in relative sea level, (2) waves from prevailing winds, (3) storm waves, including tropical cyclones and northers, (4) supply of sediment from streams, and (5) subsidence. Human activities that impact the relative positions of bay shorelines include (1) land fills, (2) riprap and seawalls, (3) size and orientation of dredged channels, and (4) subsidence caused by pumping water, oil and natural gas.

The diversity and health of bottom-dwelling animals depends on the distribution of bottom sediment types and the turbidity, i.e. the suspension of sediments, in the water column. Sediments are the carriers of both nutrients and toxicants in bay systems. Certain sediment types, such as accumulations of dead animal shells or sand, are significant economic resources. Therefore, the

Table 4.5. Species Richness of Benthic Macroinvertebrate Assemblages.

Location	Number of Species Mollusks	Polychaetes	Crustaceans
West Bay	42	48	40
Galveston Bay	32	41	29
East Bay	9	20	14
Trinity Bay	7	7	3
Clear Lake			
Houston Ship Channel	1	4	2
San Jacinto River			

Source: 1.

Table 4.6. Galveston Bay Wetland Habitat Changes, 1956-1979.

Wetland Habitat Type	1956 Acres	1979 Acres	Change Acres	Percent
Estuarine Marsh	154,588	130,139	-24,449	-15.8
Freshwater Marsh	51,496	39,119	-12,377	-24.0
Estuarine Open Water	363,213	388,397	+25,184	+6.9
Freshwater Open Water	19,648	21,939	+2,291	+11.7
Wooded	1,873	6,267	+4,394	+234.6
Streams	3,499	3,835	+336	+9.6
Beach	3,015	1,413	-1,602	-53.1

understanding of sediment dynamics becomes an important issue. The quantity of sediment contributed by streams, and where it is ultimately deposited, is inadequately known. We do not know where the sediments of eroded shorelines go or how they get there. Sediments are resuspended by waves but the details of the processes are not well known. Sediment is transported from the bay to the gulf and some is returned but the mass balance is not known.

Subsidence, shoreline erosion and changes in riverine suspended sediments have all contributed to a general loss of wetlands. It can occur as small nibbles or the loss of large tracts, indirectly or by deliberate land-use conversion. Estuarine marshes provide shoreline stabilization, maintenance of water quality by filtration of upland runoff and tidal waters, nursery habitats for economically important estuarine-dependent fisheries, and detrital materials to the bay food web. The U.S. Fish and Wildlife Service classified and quantified the wetlands surrounding Galveston Bay in 1956 and again in 1979, using aerial photo interpretation techniques. Habitat changes detectable in this manner are shown in Table 4.6. Substantial areas of brackish and freshwater wetlands were lost during the 23-year interval between surveys.

Seagrasses, never prominent, have also suffered major declines in recent years. The exact causes for this precipitous decline in seagrass habitats, from 5,200 acres in 1956 to 250 acres by 1979, will never be fully understood. The rapid industrial and residential growth of the Houston-Galveston metropolitan area is the likely cause. Increases in turbidity, pollutant runoff, vessel and boat activity, and coastal development are all suspected factors. The northern widgeon grass beds in Trinity Bay declined after construction of a power plant. The Clear Lake-Kemah-Seabrook area has become heavily urbanized. The Gulf Intracoastal Waterway and its dredged material disposal sites run adjacent to former seagrass beds on the northern short of West Bay. At least six major housing developments along the northern shore of Galveston Island were built adjacent to once-thick

grassflats. Although seagrasses may never have been a major component of Galveston Bay, they have been nearly eradicated from the estuary in less than 30 years.

Information Needs

There are many unanswered questions regarding this issue. Is land loss inevitable? If so, can man gainfully control the rate? If predicted atmospheric changes cause a greenhouse effect and contribute to a steady rise in sea level, what will be the extent of upland and wetland losses in Galveston Bay? Can new wetlands be created as fast as shorelines subside or erode? Does shoreline erosion contribute nutrients or toxicants to the bay? Can we model the processes of dredging and spoil disposal? Can dredged material be used to overcome subsidence and maintain or create wetlands? Will marshes created by man function in a similar manner as natural marshes? How long a period is required for full functioning to appear? How do natural versus created, man-made marshes compare regarding primary productivity, faunal community development, and the physical and chemical characteristics of the substrate? Are wetlands critical for fishery species, or can their functions be replaced by other habitats? Is displaced open-water habitat critical to fishery organisms? Is there an optimal open-water to vegetated-bottom ratio for estuaries, and if so, does it vary with the type of fishery organism or geographic location? Where is the nearest sand resource for beach nourishment?

Energy Production in Galveston Bay

The existence of petroleum and natural gas production facilities within Galveston Bay poses some unique environmental problems. Normal production activities create a number of **bottom disturbances.** During the exploration phase, seismic activities involve the drilling of shot holes, energy pulse damage to benthic and pelagic species, and the physical disturbance of benthic species due to "spuddown" of work barges and propwash as seismic vessels operate in shallow water (see Appendix I). Site preparation activities often require dredging of access channels to the drill site. The bay bottom is soft, unconsolidated fine-grained mud that will not support drilling platforms. Site preparation usually requires dredging down to a firm clay base, and covering the site with a 2-foot deep pad of dead oyster shell to support the drilling barge. This impacts the bottom-dwelling organisms and increases turbidity nearby. The installation and removal of pipelines further disturbs the bay bottom.

Drilling operations involve the disposal of fluids into the water column. Water used to rinse drill bit cuttings is routinely discharged into the bay. Production water, the brine produced from the wells, is also discharged into the bay, and may contain up to 25 ppm hydrocarbon material under existing Railroad Commission rules. Rig cleaning is usually performed by using bay water under high pressure to wash-down drilling barges when the drilling operation is completed. Oils and grease are washed overboard, along with quantities of drilling muds, solvents, soaps, degreasers, lubricants and other materials. The predominant drilling mud used in Galveston Bay is a barite-based compound outlawed in California for both offshore and onshore drilling due to heavy metal contamination of marine and ground waters. When a well is completed and a barge-mounted drilling rig prepares to leave the site, the bilge water is pumped into the bay to re-float the rig. Derelict structures and equipment left on-site by developers results in safety hazards and possible pollution problems. On the positive side, platforms and underwater structures provide attachment points for aquatic organisms in an environment typically poor in available solid substrates. The placement of oyster shell for drilling pads may enhance and diversify benthic communities.

Information Needs

The current and future impacts resulting from the discharge of fluids from energy production facilities need to be determined. Are the ecological impacts of energy-related bottom disturbances biologically significant? What is the cumulative impact of the concentration of production sites within this small area?

Comprehensive Assessment of Cumulative Impacts

It is readily apparent that the Galveston Bay System has been, is and will continue to be subjected to a number of external impacts that potentially may affect its productivity. Simultaneously, demand for its resources is increasing as the surrounding human population continues to grow. All ecosystems have limits on their ability to assimilate impacts. Historically, these limits have typically been unknown or unheeded until they have been surpassed. Other major estuaries—Chesapeake Bay, Delaware Bay, San Francisco Bay—have suffered major, perhaps irreversible, declines in their

productivity as the result of excessive anthropogenic impacts. With Galveston Bay we have to opportunity to act—to identify and reduce or eliminate these impacts—before it is too late.

The initial symptoms of stress have already appeared. The brown pelicans and other species have disappeared, oyster populations are greatly reduced, seagrasses are almost nonexistent, wetlands are being nibbled away around the entire bay periphery, sediment import has been drastically reduced, and freshwater inflow is threatened. Heretofore, each individual action has been judged independently, as if other development impacts do not exist. Clearly, consideration of the Galveston Bay ecosystem demands a holistic approach.

Many environmental perturbations can produce cumulative effects (10). When materials, especially toxicants, are added to the environment from multiple sources water quality can deteriorate, leading to changes in the species composition of the biota and alteration of the links in the food web. A second major type of cumulative effect can result from the repeated removal of materials or organisms from the environment. Intense fishery harvests, especially when combined with natural environmental changes, can lead to population collapse if a critical, usually unknown, threshold is passed. A third kind of cumulative effect can result from environmental changes over large areas and long periods, as, for example, extensive dredging operations and open-water spoil disposal that affect bottom habitat. More complicated cumulative effects arise when stresses of different types combine to produce a single effect or suite of effects. If channel enlargement was to resuspend toxicants and increase saltwater intrusion at the same time that freshwater inflow was reduced, salinity increases might permit invasion of oyster predators, parasites and pathogens and result in further inroads to an already depressed oyster population. Complex cumulative effects also occur when many individual areas in a region are repeatedly altered, as with periodic maintenance dredging and open-water spoil disposal. Large contiguous habitats can be fragmented into ever-smaller patches separated by inhospitable areas, making it difficult for organisms to locate and maintain populations in disjunct habitat fragments.

Cumulative impacts may also occur when perturbations are crowded in time, so close together that the effects of one perturbation are not dissipated before the next occurs. Cumulative impacts also result from disruptions so close in space that their effects overlap. Different types of disturbances occurring in the same area can interact synergistically to produce qualitatively different responses by the receiving ecological communities. Indirect effects can be produced after a perturbation has ceased, or produced some distance away from the site of initial disruption, or result from a complex intervening pathway. Incremental and decremental effects can include time and space crowding, as well as removal of habitat piece by piece, and result in a "nibbling" away of environmental quality and quantity. Threshold developments that stimulate additional activity in a region or projects whose environmental effects are delayed (time lags) or are felt over large distances (space lags) can produce cumulative effects if their impacts overlap in time or space or are synergistic with those of other developments. Examples of not just some, but **all** of these actions are planned or proposed for Galveston Bay and its watershed.

Information Need

A comprehensive assessment of the cumulative impacts of all of the present, planned and proposed projects that could affect Galveston Bay is critically needed. The assessment should be conducted by an independent third party and its design and planning must involve all of the federal and state agencies responsible for natural resource protection.

Ecosystem Interconnections

Just as phenomena occurring in the riverine and upland ecosystems feeding and surrounding Galveston Bay will affect its community structure and productivity, the bay, in turn, exerts significant effects on the Gulf of Mexico. The interactions between rivers and the bay, and between bay and gulf through the tenuous Bolivar Roads connection, require further study.

Information Needs

Many ecosystem-wide and inter-ecosystem questions need to be addressed. How will modification of freshwater inflow or saltwater intrusion affect bay circulation, temperature structure, productivity, fisheries, ecological communities, and critical habitats? The biota of the lower Trinity river habitats is dominated by marine organisms; will construction of a dam near the mouth of the river have significant impacts on marine productivity? Will an increase in wastewater discharges to the San Jacinto River drainage be functionally equivalent to the concomitant decrease in freshwater inflow from the Trinity River? How will bay and continental shelf circulation be affected by

channelization and open-bay spoil disposal? How do nutrients cycle within the bay and nearshore environments? What are the dynamics of toxic contaminants in bay and nearshelf sediments and their interaction with, and effects on, the water column and biota? How does bay and offshore primary production relate to hypoxia, coastal circulation, development of oceanic fronts and red tide phenomena? What are the biological, chemical, physical and geological exchange processes through the bay passes and the hydrographic and ecological relationship between the bay and offshore environment? How do reproduction and recruitment of fishery species relate to coastal oceanographic processes and man-induced changes in the ecosystem? What are the ecological connections between critical bay habitats and important fishery species, such as marshes, seagrass beds, oyster reefs, open bay bottom, oysters, shrimp, trout, flounder, redfish, etc. How will sea-level changes affect the ecosystem and its shoreline? What are the ecological impacts of changes in coastal erosion, sedimentation and turbidity?

Conclusions

It is apparent that a considerable volume of data involving chemical, physical and biological parameters has been gathered on Galveston Bay by several state agencies and universities but very little of the material has been compiled or analyzed. It is essential that funds and manpower be made available to analyze and interpret the existing data to provide the information needed to describe the ecological relationships of the bay system.

The uncertainties are certain to remain until further research resolves the issues. In the meantime, since the proposed developments are not time-dependent or constrained, it will be prudent to err on the side of conservation. We must avoid ecological brinkmanship, taking care not to step over the precipice. We must act to restore and enhance estuarine productivity, lest we be relegated by indifference to merely recording its decline.

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Management Issues: Galveston Bay

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LARRY MCKINNEY—Galveston Bay is the seventh largest estuary in the continental United States. It is a complex system whose physical characteristics both provide for and confound multiple-use management philosophies.

The complexity of the problem facing resource managers is evident by the contrasting uses to which the resource is subjected:

- The estuary accounts for 20 to 70 percent (depending upon species) of the total fisheries production in Texas and one-half of the state's recreational fishing expenditures.
- More than one-half of the state's wastewater discharge permits are sited within the estuary's watershed.
- Sixty to 70 percent of Texas' oyster fishery is concentrated in the estuary.
- Galveston Bay is surrounded by the eighth largest metropolitan area in the United States and, in the late 1970s and early 1980s, the fastest growing area.
- Its chief port, Houston, ranks third among United States' ports in total tonnage.
- The annual direct and induced value of the estuary's natural resources exceeds $994.7 million, and, when indirect expenditures are included in the total, annual economic benefits derived from the bay's resources are almost $3 billion.

It is for these reasons, among others, that the fate of Galveston Bay becomes a question of vital national importance.

Galveston Bay shares many problems with other estuaries of a similar stature—chiefly the rapidly escalating demands placed upon its resources because of an expanding population and associated development. Many issues, such as concerns about water quality, contaminants and habitat loss, are issues that must be addressed in practically all urban estuaries. Galveston Bay, however, is unique in the combination of two attributes:

- First, this 600 square miles of shallow, wind-dominated system, with its extensive oyster reefs, fringing marshes and open water, is being squeezed between its chief port at the head of the bay and the open sea at the other end;
- And, second, despite the competing uses, Galveston Bay outwardly remains a healthy, productive system.

Its future, however, remains to be determined. Decisions to be made in the next several years may well determine its fate, and, for managers, this may be the most critical period in its history.

The Central Management Question

The single most important question facing resource managers in this estuary is, with current and projected demands upon its resources, can Galveston Bay remain productive?

Some demands upon the system have yet to be felt. Nonetheless, the potential for an immediate and catastrophic impact from instantaneous events such as an oil or chemical spill exists on a daily

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basis. Because of the refining and chemical production facilities at the head of the bay, ships must transit the productive center of the estuary moving to and from the sea. This is a voyage of more than 50 miles. As ship size increases because of a deeper and wider channel, or as the number of transits by smaller vessels increase, an accident is likely to occur. Should, or perhaps when, this happens it is likely to be devastating to the estuaries' resources as low tidal velocities and the configuration of the system assures a high potential for damage.

Other demands upon the bay's resources have already begun to have an effect. The 251 miles of deep draft and intracoastal channels that crisscross the bay have come at the cost of almost 40 square miles of the bay impaired by channel creation and spoil disposal. This is nearly 6 percent of the bay's bottom. If proposed channel projects are completed, some 9 to 10 percent of the bay bottom, or one of every 10 acres, will have been dredged or have been impacted by dredge material disposal.

The estuary accounts for more than 40 percent of Texas shrimp landings, about $64 million in annual ex-vessel value. These organisms, along with juveniles of many important finfishes, depend on marsh habitat surrounding the bay for both forage and protection from predation. Because of this, fisheries production depends in great part on the amount of this habitat that we are able to maintain. Subsidence has contributed significantly to marsh loss. Sea level rise has probably played some role and may be more significant in the future. The impacts of these types of losses are compounded by the lack of expansion room for the creation of new marsh. Typically, as the water level rises existing marsh drowns and new marsh evolves further inland, if water depth and tidal flux are favorable, and if soil type is appropriate. The problem in Galveston Bay is that much of this productive habitat is surrounded by development, both housing and industrial. Bulkheads and filled (elevated) areas will not allow for the development of new marsh. Thus, the loss of marsh to open water proceeds without compensatory marsh creation. A significant contributing factor to these losses, and perhaps the most significant factor because of successful subsidence control efforts, is the wetlands losses due to development. Nearly 25 percent of Texas' permitted (Corps of Engineers 404/10 program) coastal development occurs within this estuary. For example, in 1987, 171 public notices for 404/10 permits were issued that requested permission to dredge or fill wetlands. These accounted for 24 percent of the annual total. If all requested permits were issued, a total of 219 acres would have been impacted (80 percent shallow open water and 20 percent marsh). Some 3.9 million cubic yards of spoil would also have been generated. Additionally, 12.7 miles of pipeline, 3.2 miles of bulkhead and 1.6 miles of piers would have been constructed.

Some of the demands on the bay's resources have already necessitated some difficult management decisions. In 1981 the Texas legislature banned the commercial fishery for red drum, or redfish as it is better known, as well as spotted seatrout in favor of a restricted recreational fishery. Basically, there were not enough fish to support both activities. Because recreational fishing is a $443 million per year industry in the estuary (based on 1986 dollars), the choice was simple. The decision, however, was a hard one because it essentially ended an industry on a statewide basis. The commercial ban continues today and through the foreseeable future. Recreational fishermen did not escape entirely. There currently is a five-fish-per-person daily limit and a "slot" or size range of 18 to 30 inches for redfish that can be retained. Above or below that slot, redfish must be released. However, there is a 10-fish-per-day limit for spotted seatrout.

A Corollary Management Question: When?

Despite these continuing pressures, Galveston Bay has remained a productive system. Consequently, both resource managers and developers have essentially gone their own way, managing their own particular piece of the pie. The system seems to have been able to absorb the competing demands and has shown remarkable resilience in responding to our use. This may no longer be the case as evidenced by the increasingly vocal disagreements between resource and development interests. The scale and number of projects proposed for the system, and the early signs of a degrading trend in key resources, have brought concerns forward and have made managers realize that important decisions are being forced on them now rather than in the future. Two important resource issues are illustrative of these concerns — the oyster fishery and freshwater inflows.

Oyster Fishery

Texas' chief oyster fishery is concentrated in Galveston Bay (60 to 70 percent). More than 90

percent of the estuary's oysters are taken from the central area of Galveston Bay proper, a relatively small area. In addition, there are numerous oyster leases onto which oysters are transferred from polluted waters and allowed to depurate before commercial harvest. Pollution has already closed 51 percent of the bay's margin because of municipal wastewater discharges, as well as non-point source discharges (see Appendix I). Following heavy rainfalls in the immediate watershed the entire bay is closed for several days, or longer, depending on the severity of the pollution load. In essence, the bay is providing tertiary waste-treatment. If this trend continues unabated, there is some speculation that more of the bay may be closed in the future. How much longer can the estuary assimilate these waste loads before the productive central oystering reefs are closed because of health hazard? This is a question that must be addressed by resource managers, perhaps sooner than we have the answers to the problem.

An additional concern is the impact of future development on this highly concentrated oyster fishery. One project, in particular, is the widening and deepening of the Houston Ship Channel (GBANS or HG50 Project). This project could so alter the bay's hydrology that 60 to 80 percent of the oyster fishery could be lost. Other equally supported estimates by the constructing agency, the Corps of Engineers (COE), minimizes the impacts at less than 10 percent. Because of disagreements about the basic validity of the salinity model employed by the COE, no resolution of these widely disparate estimates is likely. The argument may be moot, however, as health department officials fear that the hydrological changes caused by the project may also redirect polluted water outflow to encompass the irreplaceable central reefs. If that were to occur, harvest would cease altogether. Oyster lease areas would also be placed off-limits and the transplanting of oysters to "clean" areas would not be possible, or, at best, would be greatly restricted. In any event, this fishery is likely to face a severe test in the near future.

A more immediate issue has been one of the oyster fishery's status. Has it been overfished? The Texas Parks and Wildlife Department (TPWD) determined that it was and closed the 1988 season. Others have made the case that it is not, and that a closed season is not the best means to regulate the fishery. Both sides of the issue have cited substantiating data. Nonetheless, the season was closed, only to be reopened by the courts on a procedural point in January 1988. Barring flood, drought or some other extreme, time will apparently resolve who was correct on this issue.

Freshwater Inflows

A second issue, and one of the most critical ones facing resource managers in this and other Texas estuaries, is the status of freshwater inflows. The estuary depends on these inflows, primarily from rivers, as a source of salinity dilution, nutrients and sediments. A growing population and industrial development also needs water. Water that once flowed unimpeded to the estuary is now impounded and diverted to meet competing demands. How do we meet both demands? As with other important issues we have more questions than answers.

Existing reservoirs—Conroe, Houston and Livingston—have already affected freshwater inflows, both in quality and in timing. Whether their effect has been significant has not been demonstrated. Certainly, on an individual basis, and considering their relative distance from the estuary and intervening watersheds, reservoir impacts at present do not appear significant. However, three additional reservoirs are planned, Bedias, Lake Creek and Wallisville. With these additions, and in concert with the existing reservoirs, impacts could be cumulatively significant, adversely affecting the estuary. Because one of them, Wallisville, is essentially adjacent to Trinity Bay, the potential problems are greatly magnified. Not only will water be diverted from the estuary and productive habitat (approximately 5,600 acres) lost, but the reservoir will also act as a nutrient and sediment sink, denying those vital resources to the estuary.

The plants and animals of the estuary, especially the important fisheries species, have evolved to cycle with and depend upon the seasonal and flooding patterns. How will they react to man's alterations of the cycle? Can they adapt? Will different, perhaps less exploitable, species replace existing ones? These are yet to be answered questions that are extremely important to resource managers. Sabine Lake, just northeast of Galveston Bay, is a notable example of how a fishery has been altered and severely degraded by the effects of reservoirs. While a similar fate is not likely in Galveston Bay the potential for significant degradation does exist.

Another important aspect of this issue is the apparent shift of freshwater inflows from east to west. The main source of freshwater inflows to Galveston Bay historically has been from the east via the Trinity River. As Houston's population has been growing westward so has its associated return flows. These return flows are becoming an increasingly significant input of water to the bay system and may eventually exceed river flows. What is the implication to the existing salinity regime and, perhaps more importantly, existing and projected pollution problems?

It is these and the other questions that resource managers are being forced to answer. Answers that must be provided now, not in the future, because decisions about this estuary's resources are being made now, not in the future.

Current Status of Management

The governmental organization within the state is such that resource responsibilities are divided among several agencies. Additionally, there is no coordinating body or program, like a coastal zone management program, other than the state legislature or governor, with overall management responsibility for the estuary.

The following synopsis of agencies and responsibilities is illustrative of state management efforts in Galveston Bay.

Texas Air Control Board

The Texas Air Control Board (TACB) operates under statutory authority of the Texas Clean Air Act. Permits for construction or operation of any facility that has the potential to emit pollutants into the atmosphere are required, and are issued by the TACB using guidelines and performance standards contained in Board rules. Consultations are held with local pollution control agencies prior to permit issuance. All permit applications undergo a review process to evaluate facility plans and specifications prior to issuance. Operation permits must be obtained within 60 days after a facility begins operation unless an extension is granted by the Board. The TACB also does engineering studies for Point Source Discharge (PSD) permits that are issued by the U.S. Environmental Protection Agency.

Texas Historical Commission

The Texas Historical Commission (THC) is responsible for preserving and protecting the state's historical and archaeological resources, and operates under authority of the National Historic Preservation Act of 1966. Federally sponsored projects, such as reservoir construction and surface mining activities, are reviewed and permits are required by the THC as necessary to protect state resources. The Texas Antiquities Committee (TAC), a division of the THC, deals with projects not receiving federal funds and operates under statutory authority of the Texas Antiquities Code.

The TAC regulatory process plays a key role in protecting archaeological and cultural resources such as sunken ships, buried treasures, art works and prehistoric habitation sites in the coastal area (see Appendix I). The Committee issues eight types of permits covering virtually every aspect of historical and archaeological investigation, and may also require pre-project archaeological surveys to determine if sensitive resources will be affected by construction, dredging or filling activities related to private or federal projects in submerged areas. Rules and regulations established by the Committee outline detailed specifications for investigators and require comprehensive reporting of survey results.

General Land Office and School Land Board

The Texas General Land Office and School Land Board manage surface and mineral resources of state-owned lands that have been dedicated to the state's public school fund. This includes approximately 860,000 acres of uplands and 4 million acres of submerged land in rivers, bays and the Gulf of Mexico.

The three-member School Land Board, which is chaired by the Commissioner of the General Land Office, issues grants of interest on state-owned upland property for various purposes including oil and gas production, hard mineral production, hunting, timber harvest, and grazing. Permits are also issued for activities on submerged lands, including exploration and development of hydrocarbon reserves, dredging of channels, and construction of various structures such as piers, docks, wharves

and marinas. Easements are also granted for roads, transmission lines and pipeline rights-of-way on state lands. The General Land Office also has statutory authority to grant leases for public recreation, preserves and refuges, and scientific research activities on state-owned lands.

The application process for each type of permit involves an environmental review procedure and a determination of the highest and best use of state resources. This review process is coordinated with other state and federal regulatory agencies, and includes the development of contractual conditions that will protect natural resources on state lands, or provide for mitigation where environmental damage is unavoidable.

Texas Department of Health

The Texas Department of Health (TDH) administers the Molluscan Shellfish Sanitation Program and the Municipal Solid Waste Program.

The TDH's Division of Shellfish Sanitation Control is responsible for classifying coastal waters according to their acceptability for harvesting molluscan shellfish. As a result of shoreline sanitary surveys, portions of estuaries may be closed because of the actual or potential presence of contaminants. These areas are classified as "polluted" by the TDH and harvest of shellfish from them is not allowed. The department also regulates molluscan shellfish processing plants. Construction or modification of these plants require departmental certification.

The TDH issues permits for municipal solid waste disposal on the basis of performance standards contained in its rules. State law allows counties to exercise permitting authority over municipal solid waste disposal if they conform to Department requirements. As of this date, however, no counties has assumed permitting authority over municipal solid waste facilities. Where municipal and industrial wastes become mixed as part of normal collection processes, the TDH has jurisdiction over that mixed waste. An exception to this jurisdiction is Class 1 industrial waste, which must be disposed of in a facility approved by the Texas Water Commission. The Texas Water Commission also has jurisdiction over industrial solid waste.

Texas Parks and Wildlife Department

The Texas Parks and Wildlife Department (TPWD) manages fish and wildlife resources of the state by the licensing of hunting and sport fishing activities, and manages numerous programs to protect or manage fisheries resources and wetlands. The Department also plays an active role in other state and federal permit activities by reviewing and commenting on permits issued by other state and federal agencies.

The TPWD has significant legislative responsibility for wetland protection, is the state agency designated to comment on federal 404 permits, and is the state's coordinating agency for federal water development projects and permits.

The TPWD also regulates removal and/or disturbance of sand, shell or marl in state-owned waters, operates and manages an extensive system of state parks and state wildlife refuges, and administers the Texas Natural Heritage Program created in 1983 to collect and make available data on sensitive and unique natural flora, fauna and habitats within the state.

Texas Railroad Commission

The Texas Railroad Commission (TRRC) was originally created to regulate railroads, but now exercises permitting authority in many areas, including surface transportation, surface mining and restoration, and oil and gas production and transport.

Activities of the TRRC, which are of particular importance in submerged areas, include the regulation of brine discharges from oil and gas operations, enforcement of well casing and cementing requirements, regulation of well abandonment procedures, and governance of oil and gas activity reporting procedures. These activities are designed to minimize pollution in submerged areas.

Texas Water Development Board

The Texas Water Development Board (TWDB) is responsible for preparation of a State Water Plan and administers various funds that support reservoir construction and flood control projects. This plan evaluates downstream impacts of watershed alterations, impoundments and other modifications to Texas rivers and streams. State-funded reservoir construction and flood control projects

include studies that are prepared by the TWDB in cooperation with the Texas Parks and Wildlife Department to evaluate estuarine inflows and changes to bay circulation dynamics.

Texas Water Commission

The Texas Water Commission (TWC) is charged with maintaining and protecting the quality of all waters of the state, allocating state waters, and with regulating the disposal of industrial solid waste pursuant to the Solid Waste Disposal Act.

The TWC also regulates activities that may alter the course of rivers or streams in Texas, and is, therefore, involved in reviewing activities that involve clearing, channelization or draining of wetland areas.

In addition, the TWC reviews applications and issues permits for domestic and industrial sewage disposal systems. Provisions are contained in permits to ensure that discharge from the facilities will not degrade the state's water resources. The agency levies fines for permit violations or unauthorized discharges.

National Pollutant Discharge Elimination System (NPDES) permits issued by the U.S. Environmental Protection Agency to regulate disposal of waste into submerged areas must first be certified by the TWC. The TWC also issues permits for Industrial Solid Waste Disposal, and requires registration of all waste disposal sites. TWC certification is also required as part of the U.S. Army Corps of Engineers' permit process on all dredge and fill projects in jurisdictional wetlands.

TWC shares responsibility for regulating liquid and solid waste with the Texas Department of Health.

State Department of Highways and Public Transportation

The State Department of Highways and Public Transportation(SDHPT) has been designated as the local sponsor for the Gulf Intracoastal Waterway (GIWW), and is charged with providing disposal sites for dredged materials generated by periodic waterway maintenance and construction activities. The state legislature allocates funds to the SDHPT for procurement of disposal sites. The SDHPT also chairs the Gulf Intracoastal Advisory Committee, which is composed of representatives of key state agencies, industry representatives and concerned citizens groups who provide input and recommendations regarding disposal site procurement.

The primary role of the SDHPT is road construction and planning, administering funds for improvements to state highways and Texas roads that are not part of the state highway system, and administering mass transit and public transportation programs. Although the SDHPT is not a permitting agency from the natural resource standpoint, it plays a key role in the overall management and planning of coastal projects, due to its role as local sponsor of the GIWW, and the need to ensure adequate public evacuation routes during times of natural disasters such as hurricanes. The SDHPT also maintains and operates many bridges and ferries across the state.

Office of the Attorney General

The Texas Attorney General's office is the enforcement arm of the state government. Although it is not a regulatory agency per se, its involvement in coastal preservation and protection on behalf of other state agencies during litigation make it an important participant in the coastal regulation process.

The Office takes an active role in protection of the public right to beach access and brings suit on behalf of the various state agencies as needed to enforce compliance with state laws.

Management Successes

Because of the number of state and federal agencies, among whom regulation and management activities are divided, the development of policy and management goals have tended toward specific agency responsibilities, rather than toward a more comprehensive management approach. This has hampered our ability not only to provide important data to decision-makers, because the information may simply not have been collected, but also we may have failed to ask the right questions. Certainly, basic questions have remained unanswered.

Nonetheless, there have been management successes. Resource managers have not been sitting on their hands, either statewide or regionally. In many cases noticeable improvements in resource

protection and enhancement have occurred. The commitment to move forward and focus available resources on specific problems has increased dramatically in the last several years.

The Houston Ship Channel

Most notable among the efforts to quantify and mitigate the effects of pollutants on the major source of freshwater to Galveston Bay has been the effort to clean up the Houston Ship Channel. The Ship Channel was characterized as one of the 10 most polluted water bodies in the United States in the 1960s. Hundreds of industrial and domestic plants discharged an estimated 175,000 pounds per day of oxygen-demanding wastes to the waterway in 1970. Dissolved oxygen levels in the Channel Turning Basin averaged 0.25 mg/L in 1969. The monitoring station at the entrance to Galveston Bay, some 30 miles downstream of the Turning Basin, maintained an average of 5 mg/L dissolved oxygen.

Since that time, the Texas Water Commission and its predecessor water quality agencies have instituted and implemented a number of programs to clean up the channel. Not only have the oxygen-demanding materials been addressed, but also the many toxic pollutants and metals that previously went unregulated. Much more stringent wastewater permits are now in effect and are being enforced, permittees' self-reporting requirements have been expanded, intensive surveys and sediment studies have been conducted, and non-point source evaluations have been undertaken.

By 1982, point source originated biochemical oxygen-demanding loads had decreased by two-thirds to 62,000 pounds per day. According to monitoring station data, the water from the Houston Ship Channel carried approximately 8.5 mg/L dissolved oxygen to Galveston Bay, supporting an improved estuary, rookery and fishery. The water in the Turning Basin has eight times as much oxygen (2.0 mg/L) and the many harmful pollutants are now largely controlled. The best efforts of scientists, engineers and planners and the investment of millions of dollars in pollution treatment equipment have brought the Houston Ship Channel, tributary to Galveston Bay, back to life.

Protection and Enhancement of Colonial Waterbirds

While open bay spoil disposal has been the source of much controversy, there has been some benefit derived from those areas where spoil has created emergent islands. Many thousands of colonial waterbirds have taken advantage of these generally isolated areas to use as rookeries. The Texas General Land Office, Corps of Engineers and conservation groups, especially the Audubon Society, have cooperated to protect and enhance a number of critical areas.

The Gulf Intracoastal Waterway (GIWW)

This important waterway bisects the upper Galveston Bay and all of Trinity Bay from the remainder of the estuary. As with other navigation channels, maintenance dredging entails the disposal of spoil material. Disposal sites that do not affect shallow bay bottom or associated wetlands are becoming more difficult to find. Many of the existing upland sites are nearing capacity. In response to this problem the state's GIWW sponsor, the Texas Department of Public Highways and Transportation, formed the Gulf Intracoastal Waterway Advisory Committee (GIWAC) to address and prioritize problems on a coastwide basis.

GIWAC, comprised of state and federal resource agencies, has had some success in addressing this complex problem. Experimental disposal methods, spoil impact studies and site studies for new disposal areas have resulted from GIWAC efforts. Several member agencies, such as TPWD and the U.S. Fish and Wildlife Service (USFWS), have been especially active in seeking disposal alternatives. In addition, the 70th Texas Legislature appropriated $1 million to purchase or lease spoil disposal sites. GIWAC has identified the upper coast for priority consideration. All of these activities have important implications for Galveston Bay because the current means of spoil disposal there, as in several other Texas bays (open bay as opposed to upland or offshore sites), is a primary cause of habitat loss and a source of concern about resuspension of contaminants.

Freshwater Inflows

The Texas Legislature has also mandated studies, directed by TPWD and the Texas Water Development Board (TWDB), to assess the freshwater inflow needs of Texas' seven major estuarine systems. The studies are due to be completed in the next two years and should provide basic information on hydrology and productivity as related to freshwater inflows. The legislature has also

provided the means to implement study results in the form of legislation and the formation of advisory councils, one for each of the major estuaries, to develop management priority and policy. Once again, Galveston Bay is an important focus of these studies. These studies represent a significant commitment in both effort and fiscal resources to provide some important answers, not only for Galveston Bay, but for all seven of the state's major estuaries.

New Opportunities

In addition to the programs and activities just discussed, three recent actions could have significant impact on management of this estuary. It is also interesting to note that these actions originated from federal and state officials and a group of concerned citizens. It is these three entities and the actions they have taken that are key to the development of any progressive management within the estuary.

Comprehensive Study of Cumulative Impacts

Because of the number and scope of development projects, especially federal navigation and reservoir projects in and around the estuary, state and federal resource agencies have become increasingly alarmed about the future of Galveston Bay. The number of reservoirs above the estuary could be doubled, from three to six. Changes because of reservoirs, either by diversions, alterations of historic seasonal flows, or in the quality or release point of return flows could become a significant concern. The bay bottom impacted by navigation channels and spoil disposal could be increased by more than 80 percent. Potentially, one in every 10 acres of bay bottom will have been dredged or have disposed spoils if current planning is fulfilled.

As a result of growing concern, the state's major resource agencies — TPWD, TWC and GLO — have called for a comprehensive study of the cumulative impacts of all of these activities on the estuary. This request was supported by federal resource agencies — USFWS and National Marine Fisheries Service (NMFS) — and by conservation groups, such as the Gulf Coast Conservation Association (GCCA), the Sierra Club, Audubon Society and Sportsmen's Clubs of Texas (SCOT), and by resource organizations, such as the Texas Shrimp Association (TSA), Gulf Coast Fisheries Council and others. Perhaps for the first time, these many and diverse entities have joined in a common purpose: A concern for the future of Galveston Bay.

Galveston Bay — An Estuary of National Significance

Passage of the Water Quality Act of 1987 amended, and extended, the Federal Water Pollution Control Act of 1972 and its 1977 amendments, known as the Clean Water Act. The Water Quality Act formally established the National Estuary Program. A part of the Act also names Galveston Bay, along with several others, as estuaries of national significance. Texas' governor has already made the initial request to establish the required management conference. The lead agency, Texas Water Commission, with the support of TPWD, GLO and other resource agencies and academic institutions, is preparing the necessary documentation to enable the state to take full advantage of the program. This action has received widespread support from other state and federal agencies and conservation groups.

Galveston Bay Foundation

A group of prominent individuals from diverse backgrounds met in the Fall of 1987 to form an organization centered on the state's single most valuable natural resource — Galveston Bay. The Galveston Bay Foundation has quickly become a focal point for citizens concerned about the fate of this estuary. In addition, the Foundation is funding studies to answer questions about competing uses of the bay's resources. It is this type of citizen concern and active participation that is key to providing management and policy direction to those governmental agencies responsible for the estuary's resources.

Summary

The opportunity exists in the Galveston Bay system to manage its resources for multiple uses, yet not allow the system to degrade and eventually be forced into a costly recovery program as has been

necessary in Chesapeake Bay. Galveston Bay remains a relatively healthy and productive estuary, but the early warning signs of future problems are clear. Now is the time to establish the policies and goals to guide the bay's future. In Galveston Bay we certainly have a case where "an ounce of prevention is worth a pound of cure."

The issues, problems and conflicts presented in this paper, and throughout this symposium, are symptomatic of the cumulative strain being placed on the estuary's resources. The fragility of our opportunity to manage this system successfully is reflected in the short time we have to make the right decisions and, where needed, to generate the necessary information. Our options will lessen with time and decisions will have to be made, either by us or, through inactivity, they will be made for us.

As resource managers, we are in a race to not only find answers, but to ask the right questions. To do this we must tap the resources of our scientific community and work with one another as managers. In this estuary we have a resource of *national* importance. It is deserving of our *best* efforts to maintain its health, because we *cannot* afford to lose one of this *nation's* most valuable resources — *Galveston Bay.*

Summary

Terry E. Whitledge and Sammy M. Ray

TERRY WHITLEDGE—The Galveston Bay estuary has an ecosystem that has endured both the use and abuse of a highly populated urban and industrial complex and agricultural production while maintaining fisheries harvests and supporting other water-related sporting activities. There have been measurable declines in many important components in the Galveston Bay estuary and we fear that more detrimental changes will emerge in the future. The Galveston Bay complex (Trinity, Galveston, East and West Bays) is still producing a large harvest of shellfish and finfish for commercial and sports fishermen and it provides a valuable habitat for many other important species such as waterfowl and shore birds. But many of the people who know and appreciate Galveston Bay for what it was in the past and for what it is now are concerned about *what it will be in the future.* Management decisions that are being made now will determine the Galveston Bay of the future. In making these decisions, too much information cannot be provided but at this time there are many questions and even fewer answers about what should be done to protect or improve the health of Galveston Bay. Hopefully, concerned citizens, bay users, state agencies, university scientists and federal agencies can formulate a coalition that can study the problems and implement solutions and preserve the future of Galveston Bay as a national resource.

General Characteristics

All of the estuaries that are designated as being nationally significant share some common general properties that contribute to their importance. Some of the other 196 estuaries in NOAA's national estuary analysis have one or more but only a few, including Galveston Bay, will have a combination of several or all of the following properties:

1. Large Surrounding Human Population — The Galveston Bay watershed extends more than 300 miles and includes Dallas-Fort Worth as well as the Houston metropolitan areas for a combined population of about 6.8 million people. The city of Houston and related suburbs (population 2.8 million) occupy an extensive part of the shoreline of the San Jacinto River and upper Galveston Bay.
2. Area of High Growth and Development — The growth of the Houston and other surrounding areas of Galveston Bay is among the highest in the nation. This includes both permanent residences such as housing developments and tourist-related service industries.
3. Industrial Importance — The four-county area of Galveston Bay contains more than 50 percent of the total U.S. production of petrochemicals and refines more than 30 percent of the petroleum products. The port of Houston has the third largest tonnage of all U.S. ports and there are more than 4,000 vessels that transit the 50-mile long Houston ship channel each year.
4. Toxic and Eutrophic Discharges — The Galveston Bay system directly receives more than half of the permitted discharges in the State of Texas. These discharges emanate from a wide range of chemical industries and municipal wastewater treatment plants. The discharged water can contain significant concentrations of organic chemicals, petroleum byproducts, heavy metals, pathogens, nutrients, organic matter and waste heat. The Houston ship channel, in particular, has been insulted with many of these substances in the past but there has been some improvements in the past five to ten years.

5. Large Fisheries Harvest — The popularity of redfish and spotted seatrout effected a decline in these fish species so commercial harvests were banned in 1981. Sport fishermen still catch an estimated 3.2 million pounds of these organisms while commercial catches primarily rely on flounder, sand trout and sheephead. Oyster harvests fluctuate greatly from year to year depending on freshwater inflow and diseases, but the average output has remained a dominant product of Galveston Bay. Shrimp harvest both for human consumption and fish bait has continued to be a major product of Galveston Bay, which produces about 30 percent of the total Texas catch. Waterfowl hunting for geese and ducks is an important industry for the agricultural regions around Trinity and East Bays.
6. Changing Habitats — The loss of habitat may be the most profound alteration occurring in Galveston Bay because that is a direct change in the ecosystem. The saltwater marshes have diminished in size as a result of subsidence of land, water level rises, diversion of freshwater, holding of freshwater by dams and landfills and bulkheading for developments. Seagrass bed losses as high as 90 percent also mean a loss of habitat for larval and juvenile forms of important fishery species. Another important habitat change concerns the deep channels that have been dug for commercial boat traffic that allow high salinity water to enter and transit across the shallow bay. The dredge spoils from channelization produced emergent islands and dikes in Galveston Bay, which has both good and bad aspects. Finally, freshwater diversion has changed the salinity gradient in the bay system, which has a marked effect on key organisms such as oysters that need freshwater inflow to avoid marine predators and diseases. The diversion of freshwater also alters the input locations to a more urban area where biological populations are less able to cope with a multitude of insults.

Special Characteristics

Galveston Bay and other Texas estuaries have some special characteristics that contribute to their vulnerability and are partially responsible for our current lack of understanding of some of the important processes. These prominent features include:

1. Shallow Depths — The mean depth of Galveston Bay is 2.1 meters (6.5 feet). The main navigation channel is 50 miles long with a depth of 45 feet and a width of 100 feet. The undisturbed bay bottoms are very shallow with numerous reef areas.
2. High Water Temperature — The waters of Galveston Bay reach temperatures in the vicinity of 30°C in the summer months.
3. High Wind Speeds — The weather patterns produce high winds at all times of the year while the predominate direction changes from the southeast in the summer to the north in the winter.
4. Large Evaporation/Precipitation Ratio — The high summer temperatures and wind speeds combine to produce a large evaporation/precipitation ratio. In south Texas, this process makes Laguna Madre hypersaline. As the precipitation increases from west to east in Texas, Galveston Bay has nearly equal precipitation and evaporation. This factor greatly influences the salinity distribution of Galveston Bay.
5. Small Freshwater Inflow — Although Galveston Bay is located near the wettest region of the state, freshwater is a valuable resource and there is competition for that resource. Overall, about 75 percent of freshwater is used for agricultural purposes and 20 percent is allocated for industrial and domestic uses. This leaves about 5 percent for the bays and estuaries. More dams and other freshwater uses are being planned so the flow of freshwater needed to maintain the estuaries' ecosystem is in jeopardy.
6. Small Physical Circulation — The influence of tides on currents is relatively small in Texas bays. The mean tidal fluctuation is about 2 feet inside Galveston Bay while maximum range is about 2.6 feet. The wind becomes very important in both the horizontal movement and vertical mixing of bay waters. Normal tidal predictions without wind factors are not very accurate when compared to actual water heights in Galveston Bay.
7. Large Biological Production — In good years, as much as 10 to 15 percent of oyster landings in

the United States comes from Galveston Bay. Galveston Bay also contributes 31 percent of the total finfish and shellfish catch in the combined total of inshore-offshore fisheries of Texas.

Research Needs

The following research needs of Galveston Bay, developed by the Galveston Bay Seminar group, are derived from management questions and a lack of research analyses and data. The research needs are not ranked in order of importance but are grouped into general and specific categories that have been emphasized by the EPA guidelines on priority research topics in estuaries. The categories discussed are general research, toxicants, pathogens, eutrophication, habitat loss and living resources.

General Research Needs

1. Understand Water Circulation Patterns — Almost all studies of important processes in Galveston Bay would require knowledge of water movements as shown in time dependent two- or three-dimensional models. At the present time no current meter moorings have been placed in Galveston Bay; only vertical profiles using hand-held current meters have been taken over a few hours or days. Current meter moorings are necessary for testing the validity of time dependent models and they should be deployed in several diagnostic locations in the bay system.
2. Assess and Analyze Existing Data — Several state agencies, departments and boards collect data in Galveston Bay. These data sets should be coalesced and analyzed for trends and rates to the extent that is practical. The spatial and temporal resolution of the data may not be adequate for definitive results but trends may be extracted. Universities and other research organizations may be able to contribute additional data.
3. Quantify Cumulative Impacts — Multiple stresses can be placing additional impacts on the ecosystem that are not considered in tightly focused studies. For instance, upper Galveston Bay may be stressed at one location by dredging, eutrophication and permitted discharge of industrial waste. An inclusive study should be developed for each situation that would assess the total impact of the multiple stresses.
4. Delineate Ecosystem Interconnections — The river, bay and Gulf waters provide a continuum of habitats from freshwater to saltwater that is necessary for estuarine organisms. If the ecology of any of these waters is changed, the resources in the others will probably be affected. Most of the organisms in Galveston Bay utilize the habitat in more than one of these areas.

Toxicants

1. Concentration of Toxins — The concentration of toxic material in water, sediment and biota is not well known in Galveston Bay. Some values are known in the Houston ship channel, but a comprehensive survey has not been undertaken for the whole bay complex.
2. Temporal Changes — The concentration of toxicants in sediments where large values are observed has not been sampled adequately to discern temporal changes.
3. Effects on Nursery Areas — The specific effect of toxicants on nursery areas such as saltwater marshes or seagrass beds has not been adequately studied.
4. Mobilization in Dredge Spoil — Dredge spoil can either be isolated or utilized but there is a controversy over its disposal. The primary question relates to the extent of mobilization of contaminants that occur during dredging operations.
5. Biological Uptake — We may know that sediments are contaminated with toxicants but we cannot presently estimate transfer coefficients of toxic materials from sediments into organisms. Until we can estimate the rate of accumulation of toxicants in animals we will not be able to predict their effect on the biota accurately.
6. Sublethal Effects — Toxic materials may have significant effects in addition to killing organisms. Most of the endocrinology, reproduction and behavioral effects occur at lower effective concentrations of toxic materials and those effects are more subtle than death but could be just as significant.

7. Synergistic Effects — The synergistic effects of several toxicants, such as heavy metals, synthetic organic compounds and petroleum, can increase an effect to equal more than the sum of the insults. This effect may produce results that are much worse than predicted.

Pathogens

1. Current Trends — Shellfish beds and swimming areas that are closed should be assessed for current trends. Given the present discharge and runoff loading, an assessment should be made to foresee any changes in these areas.
2. Loading — An assessment should be made of the relative contribution of domestic, industrial and agricultural discharges to pathogen loading.
3. Non-Point Sources — The role of urban runoff needs to be compared to other non-point sources.
4. Accidental Discharges — An assessment of the contribution of accidental or uncontrolled (overflow) municipal discharges should be determined.

Eutrophication

1. Linear or Nonlinear Effects — The knowledge of effects of a reduction in nutrient loading is not well understood. At the present time it is known that reductions in loading decreases nutrient concentrations in upper Galveston Bay and other estuaries but it is not known whether the effects are linear or nonlinear. The addition may produce a significant lag time due to long mean residents times.
2. In Situ Regeneration — The in situ regeneration of nutrients is highly significant in shallow estuaries so the relative importance of this process compared to inputs into the bay ecosystem needs to be assessed.
3. Point and Non-Point Sources — The relative amounts of point and non-point sources of nutrient loading need to be determined. Attempts to locate estimated amounts of fertilizer application to agricultural lands have been unsuccessful due to lack of adequate records.
4. Point Source Impacts — The mini-environment around point sources receive larger insults than far-field regions. More knowledge about the severe effects near discharge points is needed.
5. Relationship to Other Processes — Nutrient loading of bay waters may have profound effects on natural processes such as denitrification, nitrification, nitrogen fixation and decomposition. The interaction of these processes in eutrophic environments is neither well known nor quantified.
6. Nutrient-Light Interaction — No comprehensive knowledge of nutrient versus light limitation of microalgae primary production in Galveston Bay is available. There are large turbidity factors from freshwater inflow and wind mixing that can be uncoupled from nutrient inputs. Other Texas bays apparently have distinct regions of light-limitation and nutrient limitation.
7. Relationship of Hypoxia to Discharges — The hypoxic events that occur in the Galveston Bay estuary are apparently related to overflows of waste treatment facilities. It is not known whether a significant background of organic loading already exists to enhance a minor discharge to cause a large impact.
8. Effects of Hypoxia and Anoxia — The overall effects of hypoxia and anoxia on the biota are not known. The possible effects range from minor mortalities to complete losses of year classes or spawning populations. The areas of impact may be small but the loss of entire populations or organisms may take years to restore.

Habitat Losses

1. Future Trends or Losses — The significant losses of Galveston Bay wetlands in the recent past have been caused by subsidence from petroleum and water extraction and a mean sea level rise. The future losses by these continued processes are not known but a prediction is needed to guide effective management strategies.
2. Creation of Wetlands — As wetlands disappear from Galveston Bay, new wetlands could be created by planned spoil disposal and other techniques. The rate of creation of new wetlands that matches the decline of submerged wetlands may be difficult to accomplish because of the conflict

with its current use by our populations. There is a related question of whether man-made marshes would function like natural marshes.

3. Habitat Substitution — If it is not possible to create new wetlands, alternate habitats like artificial reefs could be constructed. It is not known to what extent such a substitution can replace a wetland. If we do create new reef areas there is an additional concern about altering the ratio of shallow/deep water in the bays.
4. Submerged Aquatic Vegetation Losses — The cause of disappearance of 90 percent of seagrass beds in Galveston Bay is not known. Several of the possible factors range from eutrophication, turbidity from freshwater inflow or proximity to shipping lanes such as the Intracoastal Waterway to herbicides from agricultural runoff. Seagrasses were previously located in several areas of Galveston Bay so the cause may be distributed over the entire estuary.
5. Relationship to Biota — There are significant populations of waterfowl and larval fishes that utilize seagrasses for food or shelter. It is not known whether the decline in seagrass will also affect a further decline in these associated organisms.

Living Resources

1. Finfishes — The commercial fishing for redfish and spotted seatrout were closed as the population declined. The relationship of the combined effects of contaminants, loss of habitat and overfishing are not known.
2. Shellfish — There are several construction proposals that will change the timing and quantity of freshwater inflow. Dams level out the water flow with smaller peak flows and higher low flows so the prospects of future oyster and shrimp production are uncertain. Predators and disease decimate oyster populations if high salinity values occur, while white shrimp populations cannot thrive without freshwater flow. A more detailed cause/effect response needs to be shown for these impacts.
3. Resource Recovery — The living resources have declined or are threatened by toxicants, pathogens, eutrophication, habitat losses and harvesting. Many of these stresses can be reduced with good management strategies but it is uncertain how quickly the biological populations can rebound.

Keynote Address

The Honorable Lloyd Bentsen[1]
United States Senate

The Galveston Estuary—the seventh largest in the United States—has been a magnet for commerce and progress throughout the centuries.

Named in honor of Governor Galvez of Louisiana, it became a base of operations for the pirate Jean Lafitte, who called it Campeche and set out to raid Spanish commerce. When one of Lafitte's captains took it upon himself to capture and sink a U.S. merchant ship in 1820, the pirates were quickly ordered off the island by the American government.

The moment their ships cleared the harbor, American settlers began to arrive. When Texans fought the historic battle of San Jacinto, Galveston was the temporary capital. During the Civil War, this city was the chief Confederate supply port on the Gulf of Mexico, and the scene of much fighting.

We are here because we understand that the battle of Galveston Bay has taken on a new form. Today, in the 1980s, we are fighting for the survival of this estuary.

In war and in peace, during pirate raids and in periods of peaceful commerce, through hurricanes and through the centuries, the Galveston Estuary has been a source of life—and livelihood—for an entire region.

After centuries of growth and change, the delicate ecology of this estuary—and many others in the United States—hangs in the balance. Current trends, if left unchecked, could turn Galveston Bay into another Lake Erie.

When we debated the Clean Water Act in the Senate Environment and Public Works Committee, I made it a special point to see that Galveston Bay was included in the select list of priority estuaries of national significance.

Some of you here today played key roles in helping to get that designation and I look forward to working with you, through the Galveston Bay Foundation, to find honest answers to the competing demands of development and conservation. As some of you know, I am an ex-officio member of the Galveston Bay Foundation. It is dedicated to finding honest answers to the competing demands of development and conservation in and around the bay. Members of the Foundation may be divided on specific issues; they may be traditional adversaries on development questions, but they are united in a common determination to save this bay.

A comprehensive, broadly supported management plan to preserve and enhance water quality can save the estuary—and that is why we are here today.

This conference is the coming together of a wide variety of experts who have devoted a great deal of time and talent to the problems of managing Galveston Bay. The federal government is ready to help; Governor Clements' office is involved; state agencies such as Parks and Wildlife, the Water Commission and the General Land Office are committed to a cooperative, comprehensive program for the bay.

Our job is to see that Galveston Bay is healthy, fertile, rich and lovingly nurtured.

And that will be a difficult task. There are not many places I know of where you have a very fragile, delicate 600-square-mile ecosystem that provides a major source of foodfish, shellfish and game fish;

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[1]The Honorable Mr. Bentsen is Senior Senator from the State of Texas.

that is home to waterfowl and wildlife; that provides beaches, sport and commercial fishing, and recreational facilities for millions of Texas; and is surrounded by more than 3 million people living in four counties.

There is agricultural fertilizer washing into the estuary. It is traversed by hundreds of miles of ship channels. It provides access to America's third largest port. And it is virtually surrounded by petroleum, chemical and other manufacturing facilities critical to the economic well-being of our state and national economy.

As Chairman of the Senate Finance Committee, I can tell you that budget and fiscal realities make it clear that Galveston Bay will not be saved in Washington. The federal government can help. It can provide the impetus for conferences such as this. NOAA can play a role. But the hard work and the sacrifice and the tough choices will have to be made by Texans.

And that is really the way it should be. We are the ones who must accept responsibility for the destiny of a body of water that has been the source of so much life and commerce for so many centuries.

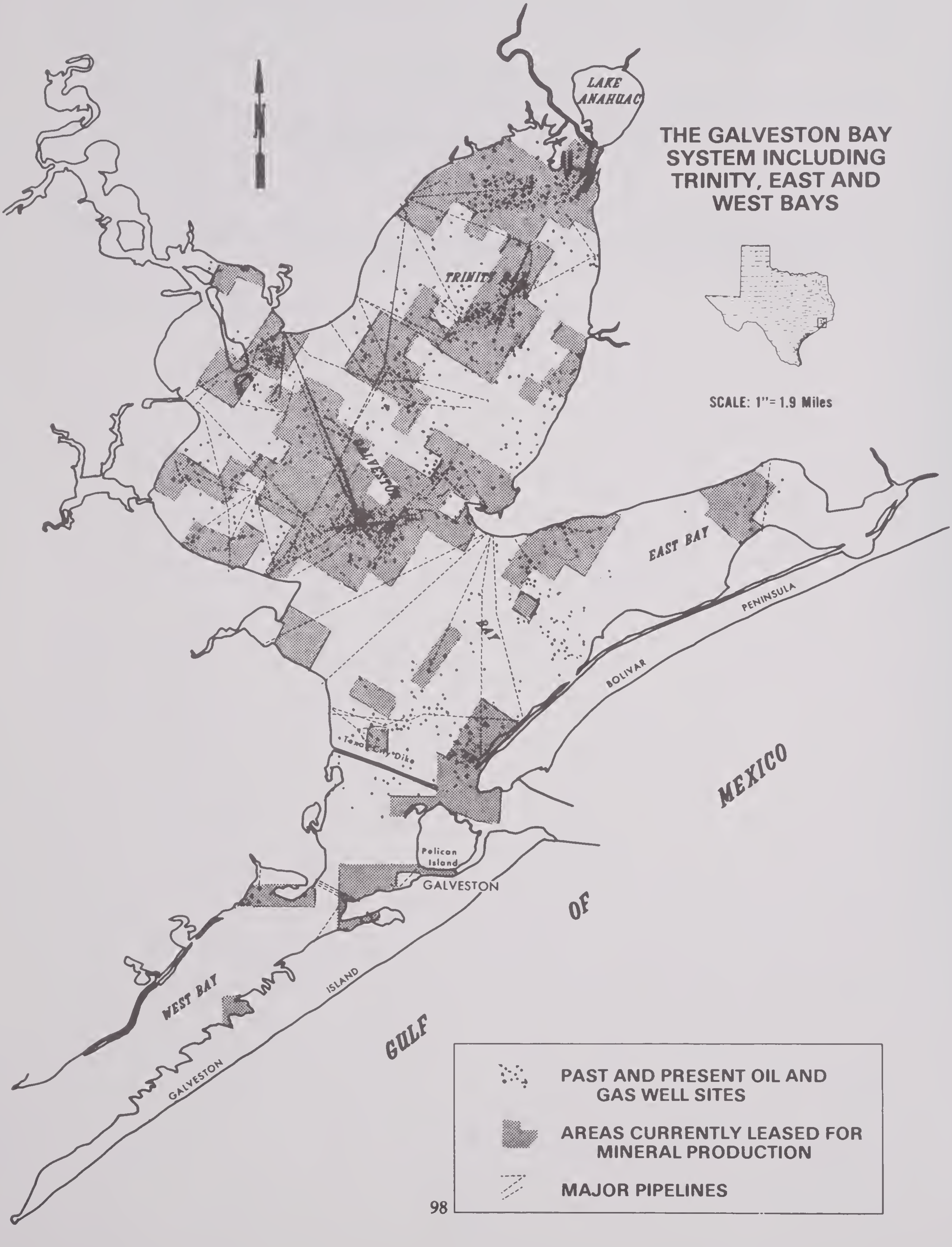
Protecting the Galveston Estuary will be a tough job, but it has to be done. Fortunately, we have the people to do it. We have Texans, working together to preserve one of our state's most important assets.

I believe the Galveston Estuary has a future as bright as its past.

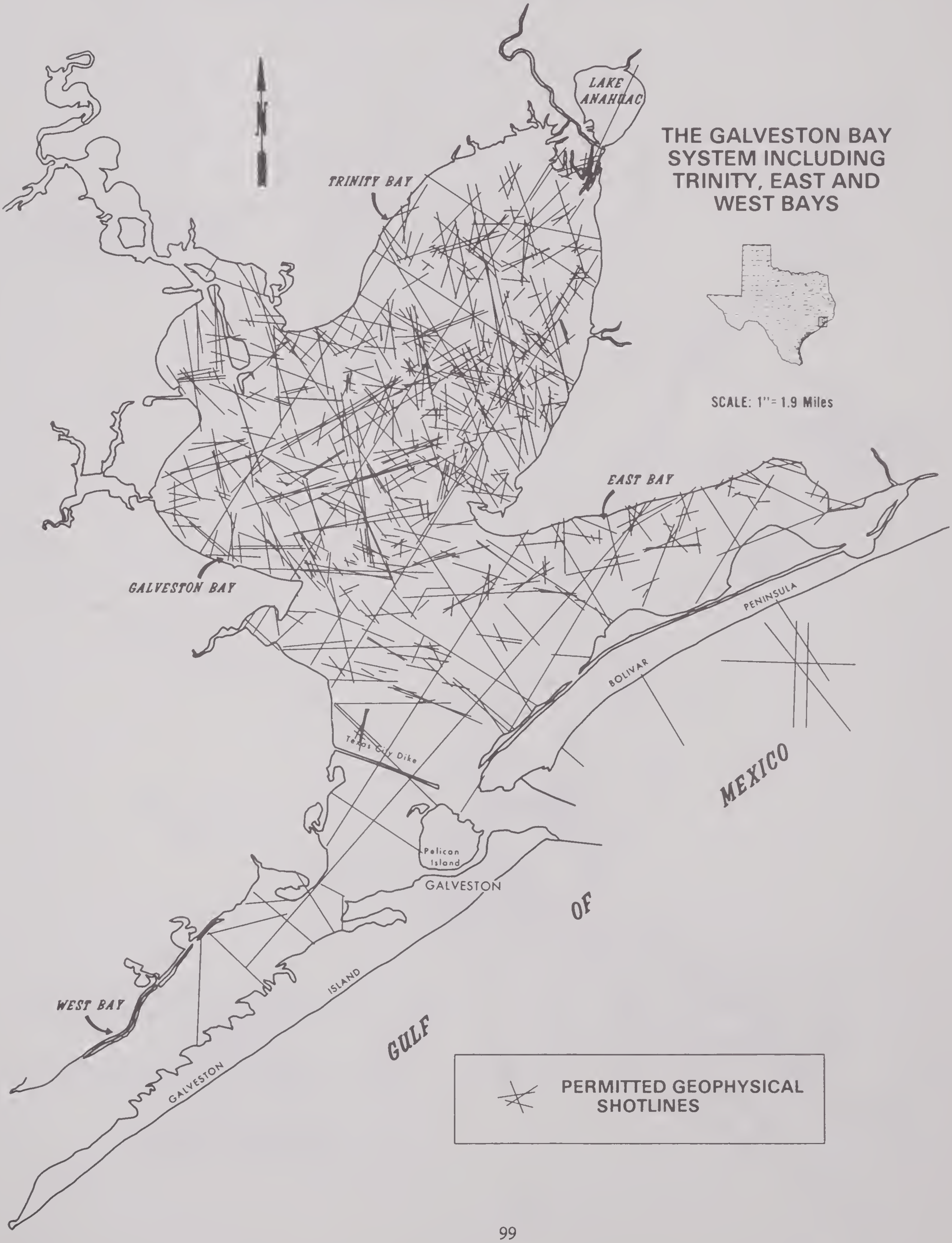
Appendix I
Supporting Figures

The following illustrations of Trinity, Galveston, East and West Bays of the Galveston Bay complex are included to accompany each segment of this proceedings.

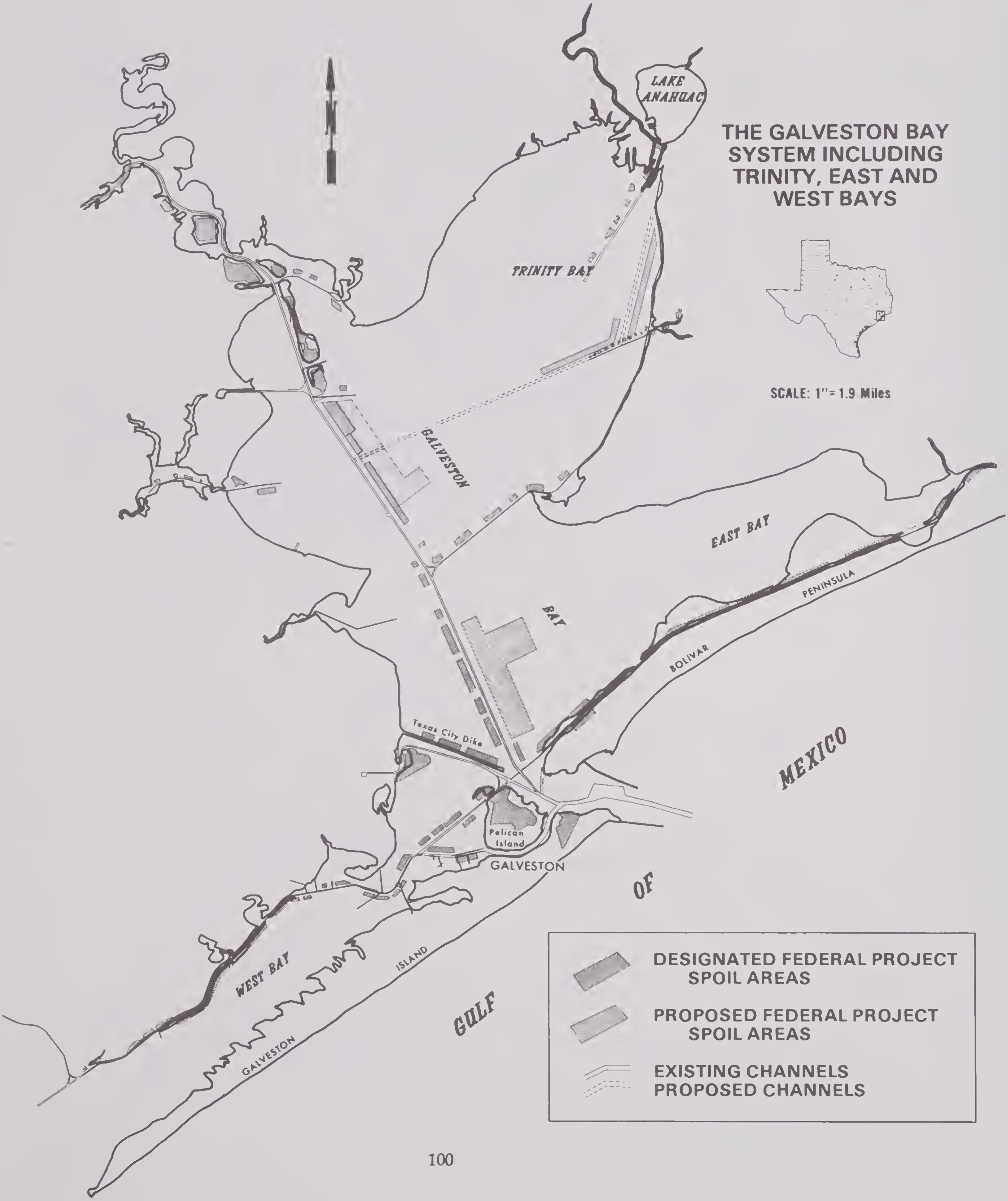
OIL AND GAS DEVELOPMENT



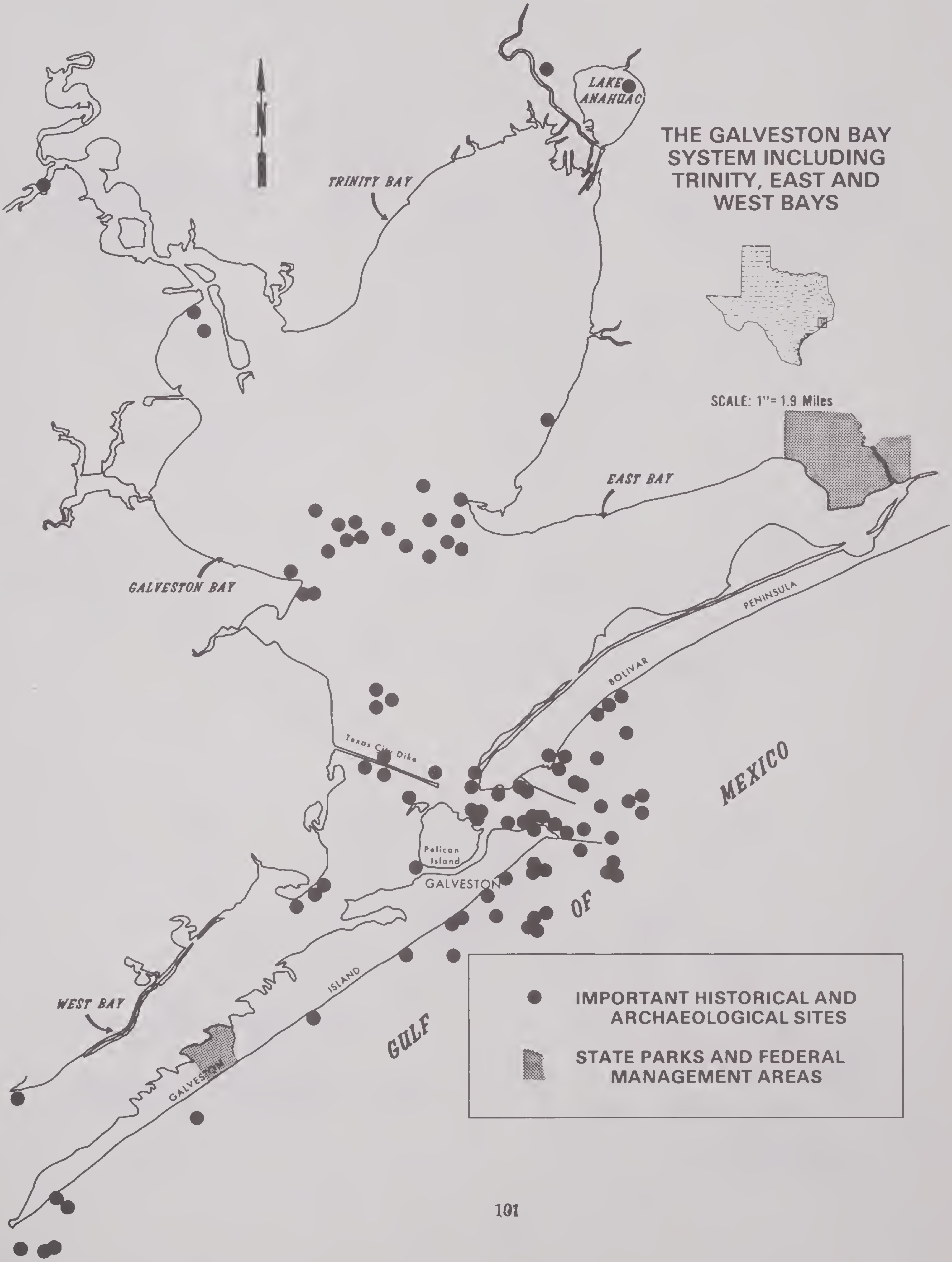
SEISMIC EXPLORATION ACTIVITY



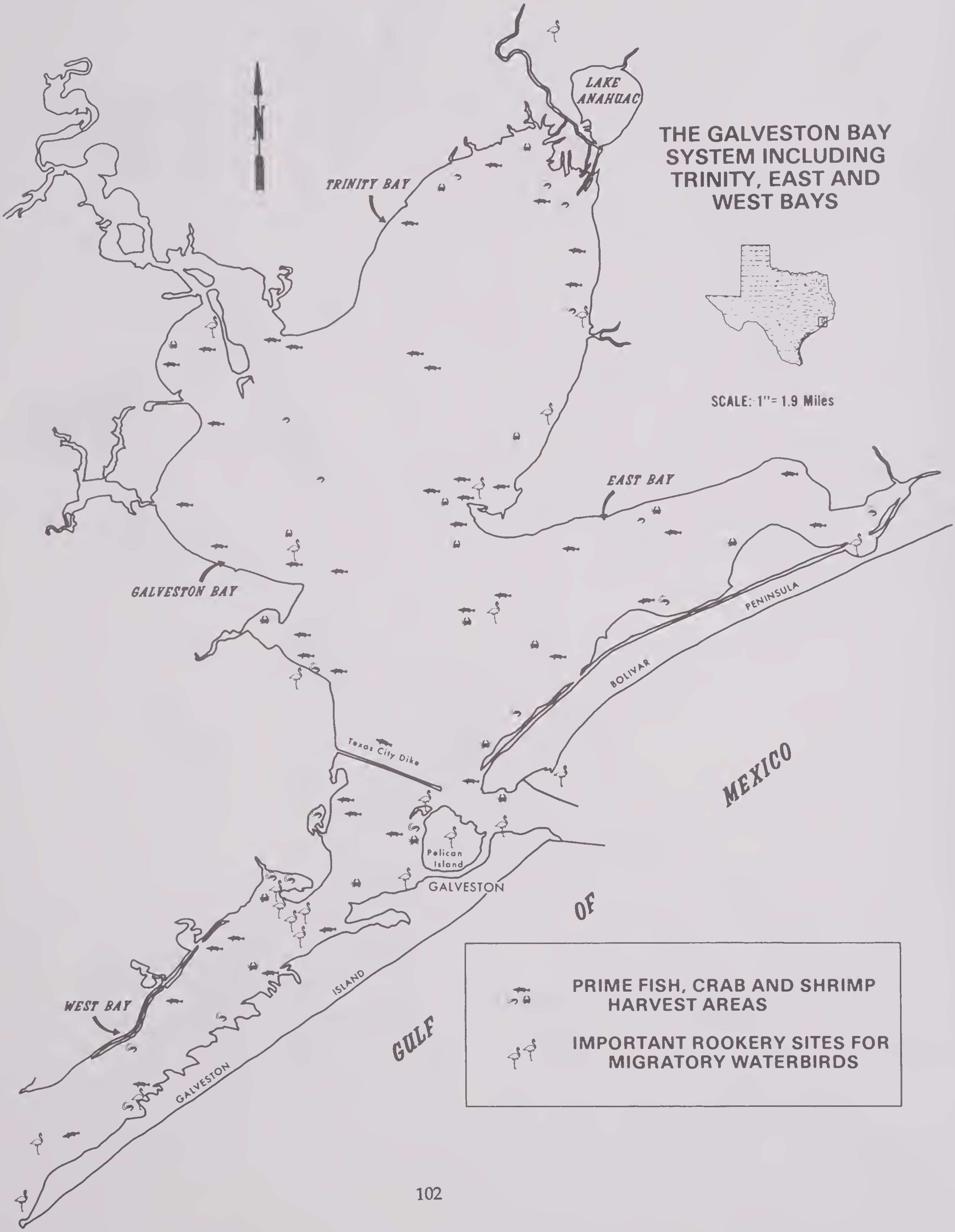
FEDERAL NAVIGATION CHANNELS AND DISPOSAL AREAS



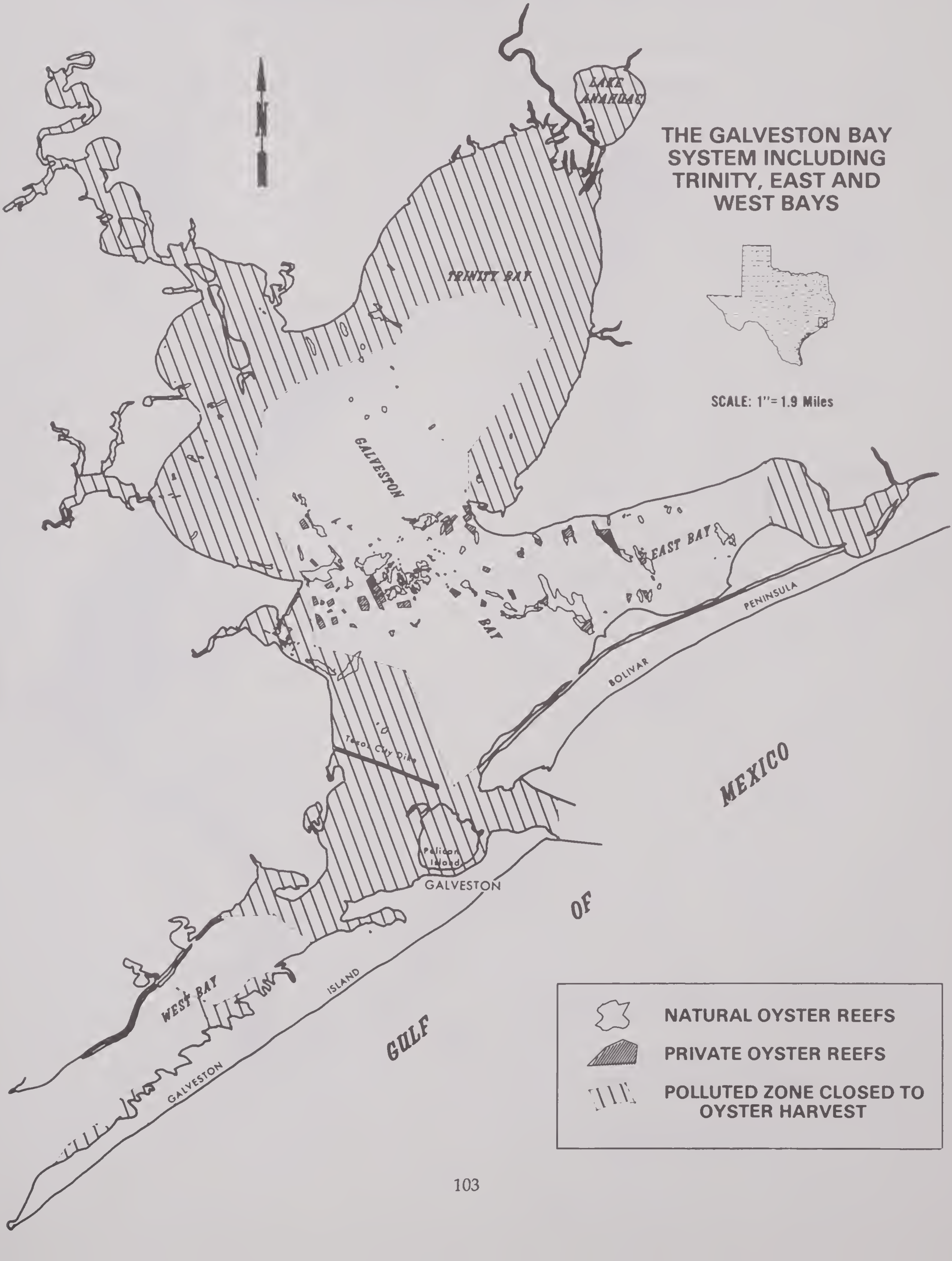
SENSITIVE CULTURAL RESOURCES



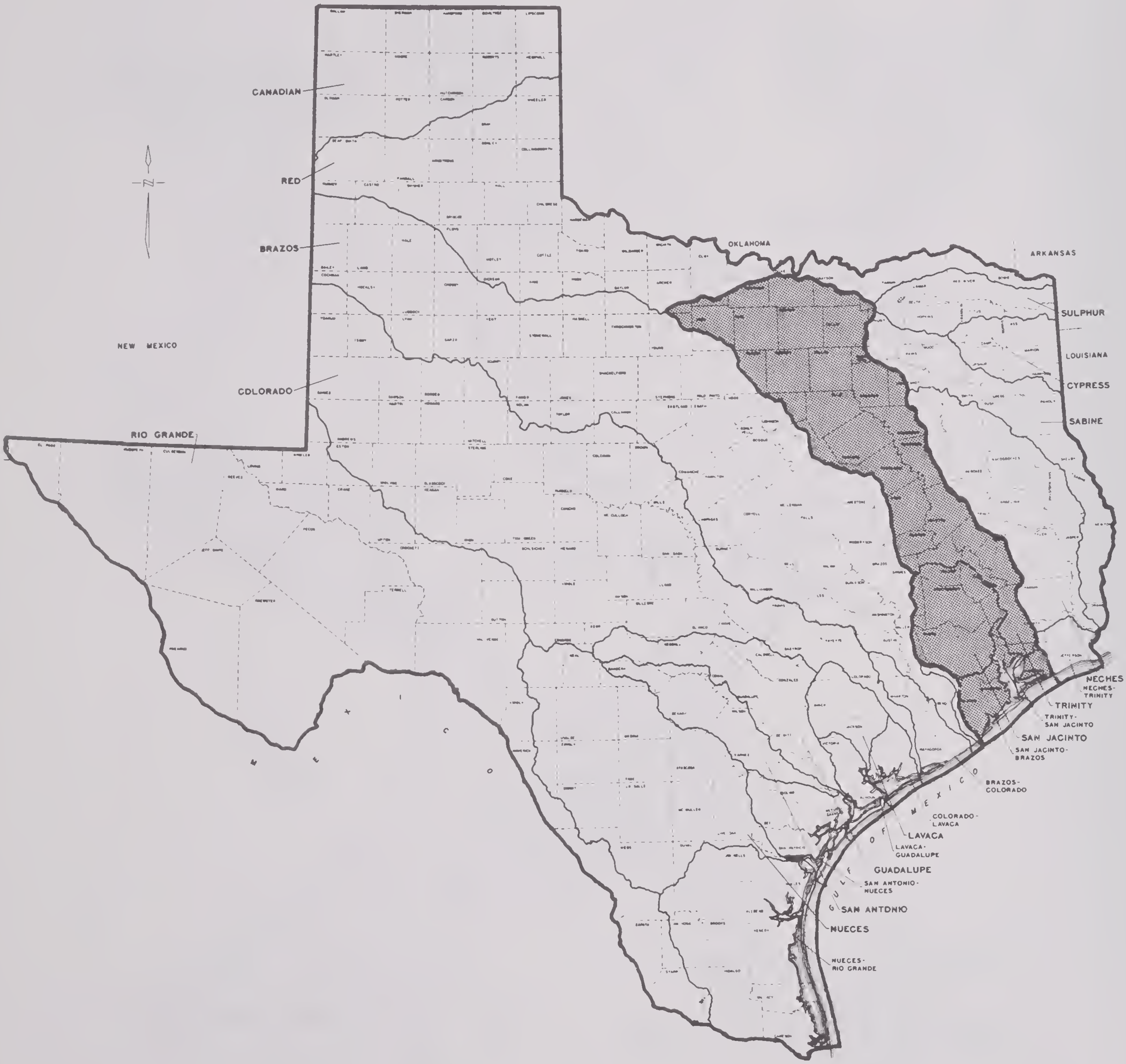
SENSITIVE BIOLOGICAL RESOURCES



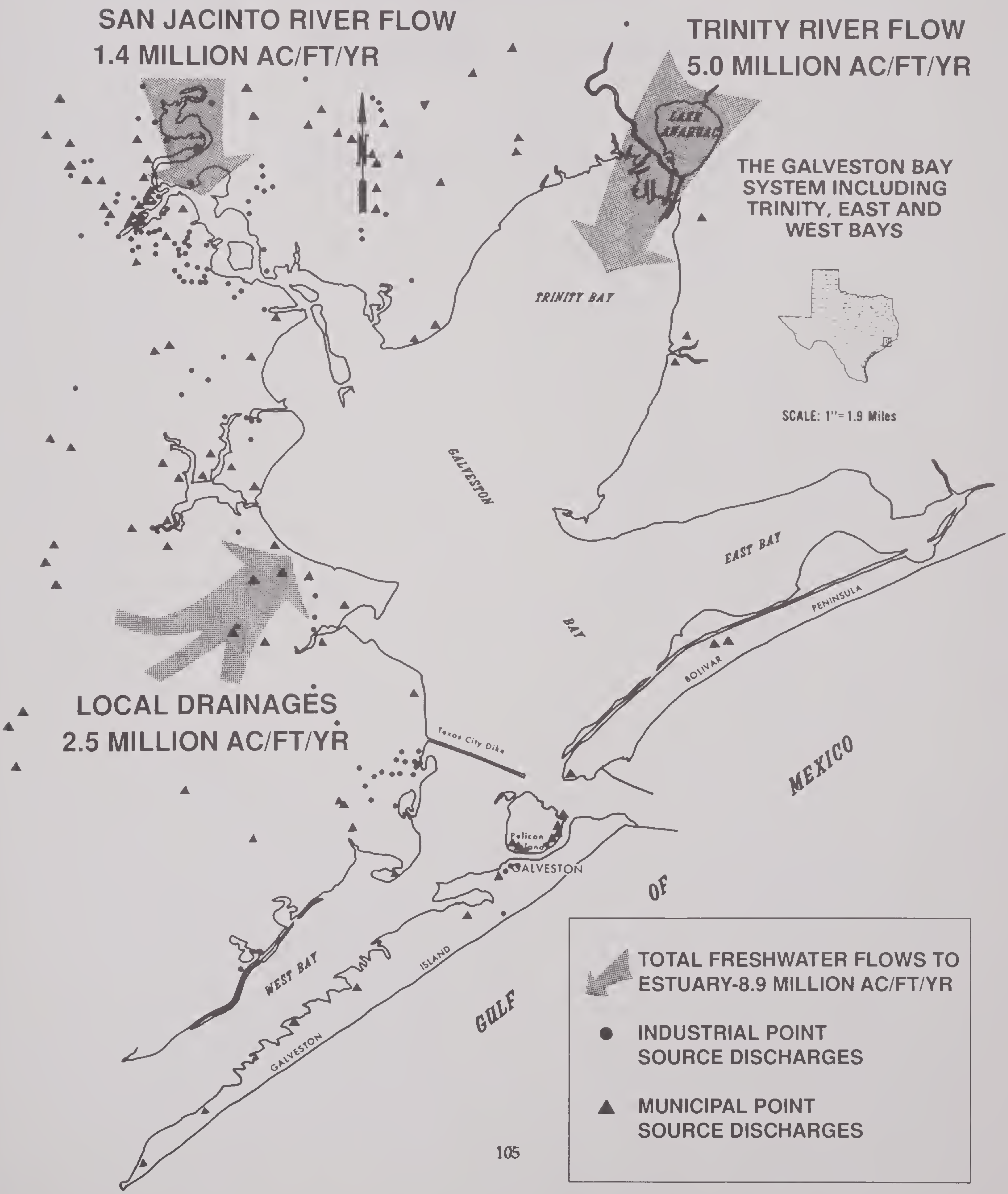
OYSTER FISHERIES RESOURCES OF GALVESTON BAY



GALVESTON BAY SYSTEM WATERSHED



FRESH WATER FLOWS AND POINT SOURCE DISCHARGES



Appendix II
Steering Committee
and
Resource Personnel

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Galveston Bay Description

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